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Program ELM: A Tool for Rapid Thermal-Hydraulic Analysis of Solid-Core Nuclear Rocket Fuel Elements

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SUMMARY

This report reviews the state of the art of thermal-hydraulic analysis codes and presents a new code, Program ELM, for analysis of fuel elements. ELM is a concise computational tool for modeling the steady-state thermal-hydraulics of propellant flow through fuel element coolant channels in a nuclear thermal rocket reactor with axial coolant passages. The program was developed as a tool to swiftly evaluate various heat transfer coefficient and friction factor correlations generated for turbulent pipe flow with heat addition which have been used in previous programs. Thus, a consistent comparison of these correlations was performed, as well as a comparison with data from the NRX reactor experiments from the Nuclear Engine for Rocket Vehicle Applications (NERVA) project. This report describes the ELM Program algorithm, input/output, and validation efforts, and provides a listing of the code.

INTRODUCTION

Program ELM calculates coolant temperature, wall temperature, and pressure profiles for a heated pipe with a compressible hydrogen flow (fig. 1) given geometry and an axial heat generation profile. This capability is desirable for accurate performance prediction of nuclear reactor thermal-hydraulics based on axial flow through passages, such as the NERVA-derivative reactor configurations with prismatic fuel elements. The program can be applied to solve iteratively for the inverse system design problem, where the maximum wall temperature or channel exit pressure and temperature are specified and the power or mass flow rate must be computed.

Program ELM was written in support of the current nuclear propulsion project for the Space Exploration Initiative (ref. 1). The program was developed as a tool to evaluate various heat transfer coefficient and friction factor correlations generated for turbulent pipe flow with heat addition which have been used in previous computer programs. During the golden era of nuclear-heated gas rocket engine development (1955 to 1972), many codes of similar capability were written in support of the NERVA/KIWI programs, the PLUTO program, and the 710 program; however, none are readily available nor adaptable for the same purpose as ELM.

SYMBOLS

A	area, ft^2	f	friction factor
C_L	pressure loss coefficient	H	static enthalpy, Btu/lb
C_P	constant pressure specific heat, Btu/lb·R	h	heat transfer coefficient, $W/ft^2 \cdot R$
D	diameter	Ht	stagnation enthalpy, Btu/lb

L length, in.

M Mach number

N dimensionless number

Nu Nusselt number

P power generation per fuel element

Pr Prandtl number

PSF axial power shape factor

Q heat flow, W

Re Reynolds number

T temperature, R

V velocity, ft/s

W mass flow rate, lb/s

X axial position, in.

ϵ surface roughness

γ ratio of specific heats

ρ density, lb/ft^3

μ viscosity, lb/ft·s

Subscripts

AW adiabatic wall condition

b bulk flow condition

CH channel

D diameter

E fuel exit condition

f film condition

H hydraulic

IN step entrance condition

ORF orifice

OUT step exit condition

W wall condition

NERVA/ROVER

Under the NERVA/ROVER program, several thermal-hydraulic fuel element analysis codes were written. The NERVA/ROVER program was a research and development project for nuclear-heated gas rocket engines sponsored by the United States Government under the auspices of NASA and the Atomic Energy Commission (AEC) (ref. 2). The NERVA space propulsion project focused on thermal-neutron fission reactors with 54-in.-long hexagonal fuel elements incorporating 19 axial coolant channels. The codes written to model fuel element thermal-hydraulics include CAC, TRACK II, TAP-A, TOSS, SCAP, and MCAP.

The Core Analysis Code (CAC) is a quasi-steady-state incompressible thermal-hydraulic analysis program written to predict the pressure and temperature through orificed fuel element channels (ref. 3). The program accounts for channel inlet and exit losses, multiple fuel elements, and radial power profile, and balances the calculated flow rate through each channel to account for core pressure-drop boundary conditions. CAC estimates the maximum material temperature. The code has been compared with NRX-A2 startup and steady-state experimental data (ref. 4). This code is currently available through the Computer Software Management and Information Center (COSMIC), the University of Georgia, Athens, Georgia 30602 (ref. 5).

TRACK II is a program for transient or steady-state thermal analysis of heat-generating solids of arbitrary geometry which are cooled by a fluid flowing through single or multiple channels (refs. 6 and 7). The hydraulic and heat convection calculations are coupled with finite-element heat conduction calculations to determine coolant conditions and material temperature distributions in a single pass. TRACK II was used for prediction of the XE-PRIME NERVA reactor performance. This code is no longer available; however, the equations used are well documented.

The TAP-A Program was developed to solve problems involving transient and steady-state heat transfer in multidimensional systems having arbitrary geometric configurations, boundary conditions, initial conditions, and physical properties (ref. 8). The program has the capability to consider the following modes of heat transfer and boundary conditions: internal conduction and radiation, free and forced convection, radiation at external surfaces, specified time-dependent surface temperatures, and specified time-dependent surface heat fluxes. This code is also no longer available, but the equations used are well documented.

The TOSS code calculates transient or steady-state material temperature distributions for a three-dimensional irregular body with internal heat generation (refs. 9 to 11). The heat transfer mechanisms of conduction and convection are considered in the code using an implicit solution method. This program is available through COSMIC (ref. 12).

The Single Channel Analysis Program (SCAP) calculates the temperature distributions in an internally cooled heat-generating solid (ref. 13). The equations used were derived for steady-state heat transfer and pressure drop for a compressible gas flowing in a coolant channel of a heater. This code is also no longer available, but the equations used are well documented.

The Multiple Channel Analysis Program (MCAP or MuCAP) calculates the temperature distributions in an internally cooled heat-generating solid (ref. 14). The equations used were derived for steady-state heat transfer and pressure drop for a compressible gas flowing in a coolant channel of a heater. Features of the code include flow balancing in parallel channels, and automatic adjustment of power or channel diameter (or loss coefficients) to meet specified uniform exit conditions. This code is also no longer available, but the equations used are well documented.

710 Program

Under the 710 program, as during the NERVA/KIWI program, many thermal-hydraulic analysis codes were written. The 710 program was a nuclear rocket engine design effort commenced by the U.S. Air Force at General Electric in the late 1950's (ref. 15). This effort was focused around a fast-spectrum-neutron fission reactor incorporating hexagonal fuel elements made of UO_2 dispersed in a refractory-metal matrix. The fuel elements contained axial coolant channels which were metal lined to provide positive fuel and fission product retention (ref. 16). The codes written under this project include THT, GFP, and ISOTHERMALIZE.

The Transient Heat Transfer (THT) program provides a solution capability for large, complex three-dimensional transient and steady-state heat transfer problems, which can include conduction, convection, and radiation, with the option to compute fluid flow rates on a one-dimensional basis (refs. 17 and 18). The final version incorporated compressible thermal-hydraulic fluid analysis capability. This code is currently available through the Energy Science and Technology Software Center (ref. 19).

The General Flow Passage (GFP) computer program calculates the one-dimensional aerothermal performance of a compressible flow in a passage of arbitrary geometry. The program computes temperatures

and pressures and accounts for entrance and exit losses. The equations used in this program are well documented, and a listing and test cases are available in reference 20.

The ISOTHERMALIZE program is a direct extension of GFP. The GFP program will vary only the mass flow rate or the inlet pressure to satisfy a given pressure drop or maximum surface temperature, whereas ISOTHERMALIZE will systematically vary two quantities, one of which may be channel diameter, in order to satisfy even more restrictive design constraints. The code includes the capability to calculate volumetric heating rates and thermal stresses. The equations used in this program are also well documented, and a listing and test cases are available in reference 21.

PLUTO Program

Under the PLUTO program, many codes were developed to compute the temperature and pressure profiles for air flow through a tube with friction and heat addition. The PLUTO program was an air-breathing nuclear ramjet development project. Under the PLUTO program, several successful tests of air-cooled reactors, TORY II-A and TORY II-C, were conducted to demonstrate the feasibility of nuclear ramjets for use at low-altitude, Mach 3 flights of up 10 hr (refs. 22 to 24). The main code written for core thermal-hydraulic analysis was the FLOSS program.

The FLOSS computer program solves a one-dimensional difference representation of momentum, energy, continuity, and state equations for turbulent, compressible gas flow in hydraulic channels (refs. 25 to 27). The program incorporates real gas analysis for air and argon. Used in the design and performance analyses of the TORY II-A test series, this code provided agreement to better than ± 5 percent for all experimentally measured parameters. The equations used in this program are well documented, and a listing and test cases are available in reference 25.

PROGRAM METHODOLOGY

The Program ELM logic is based on one-dimensional conservation of energy in combination with Newton's Law of Cooling to determine the bulk flow temperature and the wall temperature for a control volume. The control volume is an incremental length ΔL of tube. The corresponding pressure drop is then determined by applying the conservation of momentum.

A one-dimensional form of the conservation of energy is shown by the following equation for the stagnation enthalpy Ht_{OUT} exiting an incremental length ΔL of tube:

$$Ht_{OUT} = Ht_{IN} + Q/W_{CH}$$

The stagnation enthalpy Ht is defined by the following equation:

$$Ht = H + V^2/2$$

The inlet stagnation enthalpy Ht_{IN} can be computed from the inlet static enthalpy and velocity V. The inlet static enthalpy H_{IN} can be determined from the known entrance static pressure and temperature, and the velocity can be determined from the mass flow rate and the flow area. Thus, the exit stagnation enthalpy can be computed from the inlet stagnation enthalpy and heat flow per axial step $Q_{\Delta L}$. From the exit stagnation enthalpy Ht_{OUT} and an estimate of the exit pressure P_{OUT}, the exit static enthalpy and temperature T_{OUT} can be fixed.

The heat flow per axial step $Q_{\Delta L}$ is computed from the specified internal power generation per fuel element P, the specified number of coolant channels N_{CH}, and the axial power shape factor PSF

$$Q = PSF * P/(L * N_{CH}) * \Delta L$$

Since the only remaining unknown in the determination of T_{OUT} is the power shape factor, a correlation must be provided for the power shape factor in terms of known quantities. The power shape factor is typically derived from either reactor physics or experimental analyses.

Newton's Law of Cooling is shown by the following equation:

$$Q = h * A * (T_W - T_{AW})$$

The adiabatic wall temperature is defined where film conditions are evaluated at the average of the wall and adiabatic wall temperatures (ref. 28):

$$T_{AW} = T_b * (1 + 0.5 * Pr_f^{1/3} * (\gamma_b - 1) * M_b^2)$$

The form of Newton's law used to determine the wall temperature at the midpoint of an incremental step is shown by the following equation:

$$T_W = Q/(hA) + T_{AW}$$

Since we are computing T_W, a correlation must be provided for the heat transfer coefficient h in terms of known quantities.

The pressure drop across an axial step is a combination of friction and momentum loss. The form of the equation used is shown by the following (ref. 29):

$$\Delta P = [W_{CH}^2/A^2 * \Delta L * f/D_{CH} * (1/\rho_{IN} + 1/\rho_{OUT})] + [W_{CH}^2/A^2 * (1/\rho_{OUT} - 1/\rho_{IN})]$$

A correlation must also be provided for the friction factor in terms of known quantities. The following sections review a number of correlations used in the past to complete the solutions for the step exit temperature, the step midpoint wall temperature, and the step pressure drop.

Correlations for the Heat Transfer Coefficient

The heat transfer coefficients are typically correlated by using the dimensionless Nusselt number. The Nusselt number provides a measure of the convection heat transfer at the wall surface and is defined by the following equation:

$$Nu_D = hD/k$$

Many correlations for Nusselt number have been developed from experimental data for a variety of gases. The general form of the local Nusselt number correlations for turbulent pipe flow is shown by the following equation:

$$Nu_D = C1 * Re_b^{C2} * Pr_b^{C3} * (T_W/T_b)^{C4} * (C5 + C6 * (X/D)^{C7})^{C8}$$

The constants generally range from -1 to 1 and could be zero. The following paragraphs discuss the correlations included in Program ELM.

(1) Analytical solution. The first Nusselt number model was derived from an analytical solution based on turbulent velocity perturbations about a mean velocity. This equation is valid for hydrogen within ±4 percent for Reynolds numbers from 10^4 to 5×10^6 and for Prandtl numbers from 0.5 to 2000.

$$Et = (1.82 * \log_{10}Re_b - 1.64)^2$$

$$K1 = 1 + 3.4 * Et$$

$$K2 = 11.7 + 1.8 * Pr_b^{-1/3}$$

$$Nu0 = Et * Re_b * Pr_b/8/(K1 + K2 * (Et/8)^{0.5} * (Pr_b^{2/3} - 1))$$

$$Nu_D = Nu0 * (T_W/T_b)^{(-0.31*\log(TW/Tb)-0.36)}$$

(2) Wolf-McCarthy. This is the latter of two correlations developed by these researchers based on experimental data for hydrogen, helium, and air (ref. 30). The correlation shown below fits their experimental data within ±10 percent.

$$Nu_D = 0.045 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.55} * (1 + X/D)^{-0.15}$$

(3) Modified Wolf-McCarthy. This correlation is a modified version of the previous correlation by Wolf-McCarthy. The modification was done by Westinghouse AstroNuclear Laboratory for the TRACK II computer program (ref. 7).

$$Nu_D = 0.025 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.55} * (1 + 0.3 * (X/D)^{-0.7})$$

(4) McEligot and Magee. This correlation was developed at Stanford University in the early 1960's in support of the PLUTO program (ref. 31). The experimental data base is from tests with air as the fluid, and the correlation fits the data within ±10 percent.

$$Nu_D = 0.021 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.47} * [1 + (X/D)^{-0.7}]$$

(5) Worsoe-Schmidt and Perkins. The Worsoe-Schmidt and Perkins experiments were conducted with nitrogen flowing through uniformly, electrically heated Inconel tubes (ref. 32). The tests were conducted over a range of Reynolds numbers from 1.83×10^4 to 2.79×10^5 and a range of T_W/T_b from 1.24 to 7.54. The correlation is accurate to within ±20 percent of the data.

$$Nu_D = 0.024 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.7} * (1 + (X/D)^{-0.7} * (T_W/T_b)^{0.7})$$

(6) Modified Dalle-Donne. This correlation was developed for helium and air data gathered at various positions in a tube, from a length-to-diameter ratio of 10 to 240. The tests were over a range of Reynolds numbers from 3×10^4 to 4×10^5 and a range of T_W/T_b from 1.1 to 8. The correlation shown below is accurate within ±20 percent for 64 percent of the data (ref. 33).

$$Nu_D = 0.021 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.29-0.0019*X/D}$$

(7) Modified Petuhkov and Wolf-McCarthy. This correlation is a combination of the correlations developed by Petuhkov (ref. 34) and Wolf-McCarthy (ref. 7). The combination was performed by Westinghouse AstroNuclear Laboratory for the TRACK II computer program (ref. 7), and is based on the perceived accuracy of each correlation relative to axial position.

$X/D < 80$:

$$Nu_D = 0.0212 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{0.11859+0.0071465(X/D)-0.000027083*X*X/D/D}$$

$80 < X/D < 260$:

$$Nu_D = (0.0212 + 0.000211*(X - 0.2032)) * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.55}$$

$260 < X/D$:

$$Nu_D = 0.025 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.55}$$

(8) Williamson, Bartlit, and Thruston. This correlation was developed at Los Alamos Scientific Laboratory in the late 1960's and is accurate within ±20 percent for 63 percent of the data (ref. 35).

$T_W/T_b < 1.8$:

$$Nu_D = 0.023 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.765}$$

$T_W/T_b > 1.8$:

$$Nu_D = 0.023 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.2} * 0.7$$

(9) Taylor equation. The following correlation was developed by M. Taylor at NASA Lewis Research Center from hydrogen heat transfer measurements (ref. 36). The correlation was developed by using data with wall temperatures from 114 to 5600 °R and temperature ratios to 23. The correlation is valid for Reynolds numbers from 7.5×10^3 to 1.38×10^7 and is most accurate at inlet pressures higher than 530 psi. The equation is accurate within ±25 percent for 87 percent of the experimental data. The Taylor equation was used extensively by Los Alamos Scientific Laboratory in the early 1970's in developing their Small Engine Concept (ref. 37).

$$Nu_D = 0.023 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.57-1.59*D/X}$$

(10) Wolf-McCarthy II. This is the earlier of the two correlations developed by these researchers based on experimental data for a hydrogen flow in a electrically heated stainless steel tube (ref. 38). The correlation, shown below, was developed over a range of Reynolds numbers from 7800 to 1 500 000 and a range of T_W/T_b from 1.5 to 2.8.

$$Nu_D = 0.023 * Re_b^{0.8} * Pr_b^{0.4} * (T_W/T_b)^{-0.3}$$

Correlations for the Friction Factor

Many correlations for the dimensionless friction factor have been developed from analysis and experimental data for a variety of gases. However, no single correlation or equation form appears to work well across the broad range of experimental data. The following paragraphs discuss the correlations incorporated into Program ELM.

(1) Analytical solution. The first friction factor model was derived from an analytical solution based on turbulent velocity perturbations about a mean velocity. This equation is valid, for Re_w^* from 1.4×10^3 to 10^6 and for Prandtl numbers from 0.5 to 2000, within ±3 percent for hydrogen.

$$Et = (1.82 * \log_{10}Re_b - 1.64)^2$$

$$Re_w^* = 4 * W_{CH}/(\pi * D * \mu) * (T_W/T_b)^{-2}$$

$$Re' = (Re_w^*)^{-0.38}$$

$$f = Et * (T_W/T_b)^{-0.6+5.6*Re'}$$

(2) GRAPH-I-TITE G. The correlation shown below was developed by Aerojet-General Corporation for the GRAPH-I-TITE G fuel elements with a roughness of 0.006 from Reynolds numbers 2300 to 100 000 (ref. 39).

$$f = 0.25 * (0.0345 + 363/Re_b^{1.25})$$

(3) Basic friction factor. The following correlation was developed for friction factors in smooth tubes with turbulent flow. This equation is valid for data with Reynolds numbers from 5000 to 200 000.

$$f = 0.046/Re_b^{0.2}$$

(4) Moody diagram with input roughness. This correlation was developed to model the Moody Diagram for friction factor and incorporates a variable surface roughness (ref. 40).

$$f = 0.0055 * [1 + (20 * \varepsilon + 1\ 000\ 000/Re_f)^{1/3}]$$

(5) Basic friction factor and roughness correction. During analysis of channel pressure drop for the 710 Program, the basic friction factor correlation was modified by a multiplier to account for surface roughness (ref. 41).

$$f = 1.35 * (0.046/Re_b^{0.2})$$

(6) Koo equation. The following correlation is the Koo equation developed for the friction factor in a smooth tube (ref. 42).

$$f = 0.0014 + 0.125/Re_b^{0.32}$$

(7) Moody friction with $\varepsilon = 0.006$. A correlation based on the Moody diagram for a roughness of 0.006 was developed (ref. 4) and is shown in the following equation. The relative roughness of 0.006 was measured experimentally from a passage of a fuel element split axially.

$$f = 0.25 * (0.03172 + 7.2/Re_b^{0.75})$$

(8) Taylor correlation I. The Taylor correlation is presented for the friction factor in a smooth tube (refs. 43 and 44). This was developed from a data base of hydrogen, air, nitrogen, and helium experiments with a Reynolds number in the range 3000 to 187 000. The accuracy is within ±10 percent for the data base.

$$Re_w = 4 * W_{CH}/\pi/D/\mu_w * (T_b/T_W)$$

$$f = (0.0014 + 0.125/Re_b^{0.32})(T_W/T_b)^{-0.5}$$

(9) Taylor correlation II. The correlation here is the Taylor correlation incorporated in the TNT-II program, which was used to predict the performance of the NRX reactor series of the NERVA program (ref. 45).

$$Re_w = 4 * W_{CH}/(\pi * D * \mu) * T_W/T_b$$

$$f_A = 0.0014 + 0.125/(495/\varepsilon^{1.138})^{0.32}$$

$$f_B = 0.0014 + 0.125/(495/\varepsilon^{1.138}/20)^{0.32}$$

$$P = Re_w/(495/\varepsilon^{1.138})$$

$$Y = (f_B - f_A) * P^{0.3-0.1*P}$$

$$f1 = ((0.0014 + 0.125/Re_w^{0.32}) * (T_W/T_b)^{-0.5} + Y)^{0.5}$$

$$ft = (2.28 + 4 * \log_{10}[(\varepsilon + 4.675/Re_w/f1)^{-1})]^{-2}$$

$2000 < Re_w < 3000$:

$$f = ft * (Re_w - 2000)/1000 + 16/Re_w * (1 - (Re_w - 2000)/1000)$$

$3000 < Re_w$:

$$f = ft$$

(10) Moody friction with $\varepsilon = 0.004$. A correlation based on the Moody diagram for a roughness of 0.004 was developed (ref. 3) and is shown below. The relative roughness of 0.004 was measured experimentally from a passage of an unfueled element split along the axis.

$$Y = LN(Re_B * 10\ 000\ 000) + 10$$

$$f = (0.1552 - 0.04412 * Y + 0.005318 * Y^2 - 0.0002881 * Y^3 + 0.000005903 * Y^4)/4$$

Regression Models for the Axial Power Shape Factor

The axial power shape factor, which is a function of the reactor physics, is required to calculate the internal heat generation, or fission density, at each axial station relative to the average level of the entire element. For axial flow, right-circular-cylinder fission reactor cores without end-moderation, the axial power shape factor distribution is closely approximated by a sine wave. The power shape factor (PSF) values ranged from 0.2 to 1.4 for the NERVA reactors.

Program ELM incorporates eight fourth-order regression models of published power shape factor data. Figure 2 shows a sample comparison of four of the models with experimental data, while figure 3 presents a comparison of all the models. Table I presents the various regression models and their coefficients.

The regression models were developed from published experimental data for average power fuel elements (refs. 46 to 49). The general form of the fourth-order polynomial regression model which was used is shown as follows:

$$PSF = A + B^*(X/L) + C^*(X/L)^2 + D^*(X/L)^3 + E^*(X/L)^4$$

PROGRAM ELM STRUCTURE

Program ELM (ref. 50) was written in standard Fortran 77 and has been operated under a variety of operating systems on computers from IBM PC-compatibles to VAX mainframes. The overall structure and logic for Program ELM is shown in figure 4, and a listing of the program is provided in the appendix. The program listing does not include the real gas subroutine, PH2, since this model is already documented (ref. 51) or can be easily replaced by any routine which solves for density, enthalpy, molecular weight, and viscosity, given pressure and temperature. The code incorporates a user-interactive interface for selection of the three correlations and for displaying program results. Moreover, the program accesses an input file (table II) containing geometry and other parameters, and an output file (table III) containing the program results.

Algorithm

The program commences by echoing a program identification header to the screen, and this is followed by a prompt for the input and output file names. Next, the user is prompted for the number which selects the desired correlation for Nusselt number, friction factor, and power shape factor. At this point, the program reads the input file.

The first calculation made is to calculate the fuel element entrance losses. The general equation used for entrance or exit pressure loss is shown as follows:

$$\Delta P = 0.5 * C_L * \rho * V^2$$

The entrance loss coefficient $C_{L,IN}$ can be input, if known, or estimated based on the following relation, where A2 is the upstream flow area and A1 is the channel flow area (ref. 52):

$$C_{L,IN} = 1.5 - 0.5 * A1/A2 - (A1/A2)^2$$

After an initial estimate of the step exit temperature, exit pressure, and wall temperature, the code computes the current axial position. With the estimate of the exit condition and knowledge of the step entrance parameters, the bulk (average) step pressure and temperature can be computed and the gas properties can be determined by a state properties subroutine. In Program ELM, the state properties were determined by subroutine PH2. This routine calculates the state properties of parahydrogen from saturated liquid to a dissociated gas.

Once the bulk properties are determined, the Nusselt number, friction factor, and power shape factor are computed from the specified correlations. With these values, the heat flux for the step ΔL can be fixed, and the exit temperature can be determined. Since this latter parameter was initially guessed and used to compute the bulk temperature, the new exit temperature is compared to the guessed value. If the absolute difference is greater than 0.1 percent, then the bulk temperature is recomputed using the new value and the cycle iterates until convergence is met.

Once convergence on exit temperature is met, the wall temperature is computed. Since this parameter was initially guessed and used in the Nusselt number correlation, the new exit temperature is compared to the guessed value. If the absolute difference is greater than 0.1 percent, then the Nusselt number is recomputed using the new value of wall temperature, and the cycle iterates until convergence is met.

Once convergence on wall temperature is met, the step inlet and outlet gas properties are computed from the known inlet conditions, the computed exit temperature and the guessed exit pressure. Finally, the exit pressure is computed. Since this parameter was initially guessed and then used to determine exit gas properties for the calculation of exit pressure, the new exit pressure is compared to the guessed value. If the absolute difference is greater than 0.1 percent, then the exit gas properties are recomputed using the new value of exit pressure, and the cycle iterates until convergence is met.

Once convergence is met on exit pressure, the parameters computed are echoed to the screen and stored in an array, the next axial position is computed, and the entire process repeats. The process iterates until the current position equals the specified channel length. Prior to writing the parameters to the output file, the program takes care of the following bookkeeping matter.

Recall that the equations used in ELM determine the step exit temperature, the step exit pressure, and the step midpoint wall temperature. Therefore, the wall temperatures stored in the array must be corrected to the step exit location. This is done by averaging two adjacent step midpoint wall temperatures to calculate the step exit wall temperature between the midpoints. The resultant values are restored in the array, which is then written to the output file.

The last computation by the program is to calculate the fuel element exit pressure loss. The exit loss coefficient $C_{L,OUT}$ can either be input or be calculated from the following relation, where A1 is the channel flow area and A2 is the downstream flow area (ref. 52).

$$C_{L,OUT} = 2 * [A1/A2 - (A1/A2)^2]$$

Program Input Description

The main program input is read from a file assigned to Fortran unit 2. This file contains the geometric and initial hydrogen state parameters required for a successful program execution. The first 65 columns of each input file line contains a brief description of the parameter which follows in the next 14 columns. The following sections describe each input parameter.

POWER. Total thermal power added to the hydrogen for the fuel element, units are in watts.

PIN. Plenum pressure at the fuel element entrance, in pounds per square inch.

TIN. Plenum temperature at the fuel element entrance, in degrees Rankine.

WCH. Total mass flow rate through the fuel element, in pounds per second.

DH. Coolant channel hydraulic diameter, in inches.

NCH. Number of coolant channels bored through each fuel element. This is a dimensionless parameter.

L. Total length of the fuel element, in inches.

DL. Computational length into which the fuel element will be divided, in inches.

EROUGH. Channel surface roughness, in inches. This parameter is only required by friction factor correlations 4 and 9.

CLIN. Channel entrance loss coefficient. This is a dimensionless parameter. There are two options with CLIN. First, if CLIN is greater than zero, then this value will be used. Second, if CLIN is less than or equal to zero, it will be calculated internally from DH and DFE.

CLOUT. Channel exit loss coefficient. This is a dimensionless parameter. There are two options with CLOUT. First, if CLOUT is greater than zero, then this value will be used. Second, if CLOUT is less than or equal to zero, it will be calculated internally from DH and DFE.

DFE. Distance across the flats of a hexagonal fuel element, in inches. This parameter is required if either CLIN or CLOUT is less than zero.

DORF. Channel entrance orifice diameter, in inches. This parameter will be used instead of DH to compute the entrance loss coefficient if CLIN is less than zero.

VALIDATION

In order to visually understand the differences between the various heat transfer coefficient correlations, figures 5 and 6 present a comparison of the wall temperature distributions computed from each of the correlations within ELM. To visualize the effects of the various friction factor correlations, figures 7 and 8 present a comparison of the pressure distributions computed from each of the correlations within ELM. Note that correlations 1 and 4 in figure 7 do not follow the trends of the other eight correlations.

Because the most important aspect of any analysis program is its ability to accurately predict performance, Program ELM was validated against steady-state wall temperature data from the NRX reactor experiments of the NERVA program. These wall temperature data were from fuel elements located at the midrange radius; therefore, the power level and mass flow rate were close to the reactor average in light of the radial power profiles. Since the power generated per fuel element at the midrange radius is not precisely known, Program ELM was executed iteratively (while varying power) to match the known fuel element exit temperature T_E. The fuel element exit temperature was measured within ± 100 °R. An input parameter sensitivity study was conducted, and the results are shown in figure 9. In this study, all input variables were held constant except for the parameter under evaluation. The results indicate the strong effect of power and mass flow rate on wall temperature, and a moderate effect of hydraulic diameter on pressure drop.

Figure 10 presents the results of the validation effort. This figure compares fuel element wall temperatures from several NRX reactor experiments with Program ELM analysis generated to match fuel element exit conditions. The experimental data were collected by thermocouples imbedded within the coolant channel wall. Included in this figure are the results from executing this code at power levels to produce fuel element exit temperatures ± 100 °R from the nominal. The Program ELM input and output data for the NRX-A3 reactor (ref. 53) are shown in tables II and III, respectively; for the NRX–A4 reactor (ref. 54) in tables IV and V, respectively; for the NRX–A5 reactor (ref. 48) in tables VI and VII, respectively; and for the NRX–A5 reactor in tables VIII and IX, respectively. In all cases, correlation 2 (Wolf-McCarthy I) for the heat transfer coefficient and correlation 2 (GRAPH–I–TITE G) for the friction factor were used.

Each comparison in figure 10 shows the calculated wall temperatures below the experimental data. This error can be attributed to either the use of imbedded thermocouples to represent wall temperatures or the roughness of the estimate for average fuel element mass flow rate. Figure 9 illustrates the large effect of mass flow rate variations.

CONCLUSIONS

A program has been developed and validated for modeling the steady-state pressure drop and temperatures along an axial coolant channel with heat transfer to a compressible fluid. Program ELM was used to evaluate various heat transfer coefficient and friction factor correlations on a common basis. As validation, ELM was used to model NRX reactor coolant channels. The results from this analysis were compared with experimental data for fuel element coolant channel wall temperature. The comparison showed good agreement. Since ELM is small, fast, accurate, and portable, it can be used as a rapid approximation tool for fuel element parametric studies. Moreover, ELM can be used to analyze general flow through pipes with high wall heating rates.

APPENDIX.—PROGRAM LISTING

```
      PROGRAM ELM
CC
CC    THIS PROGRAM PERFORMS AEROTHERMODYNAMIC ANALYSIS ON H2 GAS COOLED
CC    NUCLEAR REACTOR CORE FUEL ELEMENTS.  THE ANALYSIS IS BASED ON
CC    CONSERVATION OF ENERGY EQUATIONS WITH EXTENSIVE USE OF CORRELATIONS
CC    FOR THE CONVECTIVE HEAT TRANSFER COEFFICIENT, FRICTION FACTOR, AND
CC    ELEMENT AXIAL POWER DISTRIBUTION.  THE ANALYSIS IS FOR AN AVERAGE
CC    COOLANT CHANNEL, SUCH AS AT A POINT IN THE CORE WHERE THE RADIAL
CC    POWER OVER AVERAGE POWER RATIO IS UNITY.
CC
CC    THIS PROGRAM IS AVAILABLE THROUGH NASA'S COMPUTER SOFTWARE LIBRARY,
CC    COSMIC, @ (404) 542-3265 AS PROGRAM # LEW-15423.
CC
CC    THE SUBROUTINE PH2 IS AVAILABLE THROUGH COSMIC AS LEW-15505.
CC
CC    CURRENTLY:
CC       1) NO ELEMENT ENTRANCE OR EXIT LOSSES ARE ACCOUNTED FOR.
CC       2) THE CHANNEL DIAMETER IS ASSUMED TO BE CONSTANT.
CC       3) CONVERGENCE TOLERANCES ARE SET TO 1 DEGREE RANKINE AND 1 PSI.
CC
CC    ORIGINATION: SEPTEMBER 12, 1991
CC    LAST MOD:    APRIL 30, 1992
CC
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 L,K,NU,NCH,NUSELT,MACH
      DIMENSION STORE(5000,7)
      CHARACTER DATE*20
      DATA PCONV/0.001/,TCONV/0.001/,HCONV/0.00001/
      DATA VERSION/1.03/,                DATE/'APRIL    30, 1992'/


C.....OUTPUT PROGRAM BANNER TO SCREEN AND REQUEST I/O FILE NAMES
      CALL BANNER(VERSION,DATE)

C.....SELECT NUSSELT NUMBER CORRELATION
      INU   = 0
      INU   = NUSELT(DUM1,DUM2,DUM3,DUM4,DUM5,DUM6,INU)
C.....SELECT FRICTION FACTOR CORRELATION
      ICF   = 0
      ICF   = CFRICT(DUM1,DUM2,DUM3,DUM4,DUM5,DUM6,DUM7,ICF)
C.....SELECT POWER SHAPING FACTOR CORRELATION
      IPSF  = 0
      IPSF  = PSFCAL(DUM1,IPSF)

      WRITE(6,1) VERSION,DATE
      WRITE(3,1) VERSION,DATE
    1 FORMAT('                          PROGRAM ELM',/,
     1 '                      VERSION ',F5.2,/,
     1 '                    ',A20,/)

C.....READ INPUT IN ENGLISH UNITS
      CALL READER(TIN,PIN,DH,POWER,NCH,WCH,L,DL,EROUGH,CLIN,CLOUT,
     1          DFE,DORF)
      WRITE(6,2)
      WRITE(3,2)
    2 FORMAT(
     1 1X,'  X (in.)','    Tb (R)','    Tw (R)',' Cum. P(W)',
```

```
     1 '     Re  ',' Pb (psi)','     MACH ',/,
     1      1X,' --------',' --------',' --------',' ---------',
     1 ' --------',' --------',' ---------')

C.....CONVERT INPUT
      TIN    = TIN/1.8
      PIN    = PIN * 6894.7572
      DH     = DH  *   0.0254
      DFE    = DFE *   0.0254
      DORF   = DORF*   0.0254
      WCH    = WCH *   0.45359237/NCH
      L      = L   *   0.0254
      DL     = DL  *   0.0254
      EROUGH = EROUGH* 0.0254
C.....INITIALIZATION
      ISTEP  = 1
      QSUM   = 0.
      TBN    = TIN
      TWN    = TIN
      X      = -DL/2.
      AREA   = 3.14159*DH*DL
      WOA2   = (WCH/(3.14159*DH*DH/4))**2
C.....COMPUTE ENTRANCE AND EXIT LOSS COEFFICIENTS
      AFE    = 1.5*DFE*DFE*0.57735
      IF (DORF.LE.0.) DORF = DH
      ADH    = 3.14159*DORF*DORF/4.*19.
      IF (CLIN.LT.0.)  CLIN  = 1.5-0.5*ADH/AFE-(ADH/AFE)**2
      IF (CLOUT.LT.0.) CLOUT = 2.*(ADH/AFE - (ADH/AFE)**2)
C.....COMPUTE ENTRANCE LOSSES
      IDUM   = 0
      CALL PH2(DUM1,PIN,TIN,RHO,VIS,CP,DUM2,DUM3,DUM4,DUM5,IDUM)
      U      = 4.*WCH/RHO /3.14159/DH/DH
      PIN    = PIN - CLIN*RHO*U*U/2.
      PBN    = PIN
      POUTN  = PIN - 30000.
      WRITE(6,8000) 0., TIN*1.8, TIN*1.8,0.,0.,PIN/6894.7572,0.
      WRITE(3,8000) 0., TIN*1.8, TIN*1.8,0.,0.,PIN/6894.7572,0.

C.....BEGIN ITERATION
  100 X      = X + DL
C.....DETERMINE FLOW PROPERTIES USING BULK STATIC TEMPERATURE AND
C     BULK STATIC PRESSURE
  200 TB     = TBN
      PB     = PBN
      IDUM   = 0
      CALL PH2(DUM1,PB,TB,RHOb,VIS,CP,PR,SOS,K,DUM5,IDUM)
      U      = 4.*WCH/RHOb/3.14159/DH/DH
      MACH   = U/SOS
      REb    = RHOb*U*DH/VIS

  300 TW     = TWN
C.....COMPUTE NUSSELT NUMBER
      NU     =  NUSELT(REb,PR,TW,TB,X,DH,INU)
      HTC    = (K/DH)*NU
C.....COMPUTE FRICTION FACTOR
      f      =  CFRICT(REb,TW,TB,DH,EROUGH,PB,WCH,ICF)
C.....COMPUTE POWER SHAPE FACTOR
      XOL    = X/L
      PSF    = PSFCAL(XOL,IPSF)
C.....COMPUTE POWER ADDED TO FLOW ACROSS STEP
```

```
      Q     = PSF*POWER/L/NCH*DL
C-----------------------------------------------------------------
C-------------------------COMPUTE TOUT------------------------------
C-----------------------------------------------------------------
C.....THE FOLLOWING SECTION COULD BE REPLACE BY THE COMMENTED-OUT
C     EQUATION FOR 'TOUT'
C.....COMPUTE STATIC ENTHALPY AT BEGINNING OF EACH STEP
      IDUM  = 0
      CALL PH2(HIN,PIN,TIN,RHOIN,DUM1,DUM2,DUM3,DUM4,DUM5,DUM6,IDUM)
      HOUTN  = HIN
C.....COMPUTE VELOCITY AT BEGINNING OF EACH STEP
      UIN   = 4.*WCH/RHOIN/3.14159/DH/DH
C.....COMPUTE ENTRANCE TOTAL ENTHALPY
      HTIN  = HIN + UIN*UIN/2.
C.....COMPUTE EXIT TOTAL ENTHALPY
      HTOUT  = HTIN + Q/WCH
C.....COMPUTE EXIT STATIC ENTHALPY & TEMPERATURE
  350 HOUT   = HOUTN
      IDUM  = 1
      CALL PH2(HOUT,POUTN,TOUT,RHOOUT,DM1,DUM2,DUM3,DUM4,DUM5,DUM6,IDUM)
      UOUT   = 4.*WCH/RHOOUT/3.14159/DH/DH
      HOUTN  = HTOUT - UOUT*UOUT/2.
      IF (ABS((HOUTN-HOUT)/HOUT).GE.HCONV) GOTO 350

C     TOUT   = Q/WCH/CP + TIN
C.....COMPUTE NEW BULK TEMPERATURE
      TBN    = (TOUT+TIN)/2.
      IF ((ABS(TBN-TB)/TB).GE.TCONV) GOTO 200

C-----------------------------------------------------------------
C-------------------------COMPUTE TW------------------------------
C-----------------------------------------------------------------
C.....COMPUTE ADIABATIC WALL TEMPERATURE
      Taw    = TB
  400 Tf     = (TW + Taw)/2.
      IDUM  = 0
      CALL PH2(DUM1,PB,Tf,RHOf,DUM2,CPf,PRf,DUM4,DUM5,DUM6,IDUM)
      GAMH2  = 1./(1.-4949.999/CPf)
      Taw    = TB*(1.+PRf**0.3333*(GAMH2-1)/2.*MACH*MACH)
      TfN    = (TW + Taw)/2.
      IF ((ABS(TfN-Tf)/Tf).GE.TCONV) GOTO 400

C.....COMPUTE WALL TEMPERATURE
      TWN    = Q/HTC/AREA + Taw
      IF ((ABS(TWN-TW)/TW).GE.TCONV) GOTO 300

C-----------------------------------------------------------------
C-------------------------COMPUTE POUT------------------------------
C-----------------------------------------------------------------
C.....COMPUTE PRESSURE DROP
      XX     = X + DL/2
C.....COMPUTE RHO,IN FOR USE IN P,DROP EQUATION
      IDUM  = 0
      CALL PH2(DUM1,PIN,TIN,RHOIN,DUM2,DUM3,DUM4,DUM5,DUM6,DUM7,IDUM)
C.....COMPUTE RHO,OUT FOR USE IN P,DROP EQUATION
 1000 POUT   = POUTN
      IDUM  = 0
      CALL PH2(DUM1,POUT,TOUT,RHOOUT,DUM2,DUM3,DUM4,DUM5,DUM6,DUM7,IDUM)
      dP     = (WOA2*(DL*f/DH)*(1./RHOIN+1/RHOOUT))+
     1         (WOA2*(1/RHOOUT-1/RHOIN))
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      POUTN  = PIN - dP
      IF ((ABS(POUTN-POUT)/POUT).GT.PCONV) GOTO 1000
      PBN    = (POUT+PIN)/2
C.....ITERATE UNTIL NEW BULK EQUALS OLD BULK (RECALL THAT INITIALLY
C     TWALL IS COMPUTED WITH GUESSED BULK PRESSURE)
      IF ((ABS(PBN-PB)/PB).GE.PCONV) GOTO 200
C.....ROUGH ESTIMATE FOR BULK PRESSURE OF NEXT STEP
      PBN    = POUT + dP/2.

C.....STEP PROPERTIES CONVERGED
      WRITE(6,8000) XX*39.3701, TOUT*1.8, TW*1.8,QSUM,REb,POUT/6894.7572
     1            ,MACH
      QSUM   = QSUM + Q
      STORE(ISTEP,1) = XX*39.3701
      STORE(ISTEP,2) = TOUT*1.8
      STORE(ISTEP,3) = TW*1.8
      STORE(ISTEP,4) = QSUM
      STORE(ISTEP,5) = REb
      STORE(ISTEP,6) = POUT/6894.7572
      STORE(ISTEP,7) = MACH
      ISTEP  = ISTEP + 1
      IF (ISTEP.GT.5000) WRITE(6,*) ' ERROR - TOO MANY STEPS FOR ARRAY',
     1                      ' STORE, PLEASE INCREASE ITS SIZE.'
      TIN    = TOUT
      PIN    = POUT
      IF ((XX+DL/2).LT.L) GOTO 100
C.....CORRECT FOR EXIT LOSSES
      U      = 4.*WCH/RHOOUT /3.14159/DH/DH
      POUT   = POUT - CLOUT*RHOOUT*U*U/2.
      STORE(ISTEP-1,6) = POUT/6894.7572

C.....CORRECT WALL TEMPERATURE FROM STEP MIDPOINT TO STEP EXIT BY AVERAGING
      DO 7990 I = 1, ISTEP-2
            STORE(I,3) = (STORE(I,3)+STORE(I+1,3))/2.
 7990 CONTINUE
C.....CORRECT EXIT WALL TEMPERATURE BY EXTRAPOLATING
      STORE(ISTEP-1,3) = STORE(ISTEP-1,3) +
     1               (STORE(ISTEP-1,3)-STORE(ISTEP-2,3))/2
      WRITE(3,8000) ((STORE(I,J),J=1,7),I=1,ISTEP-1)
 8000 FORMAT(1X,4F10.2,F10.0,F10.2,F10.3)
      WRITE(6,8010) QSUM*NCH
 8010 FORMAT(31X,'----------',/,31X,F10.1,' = POWER/ELEMENT',/)
      WRITE(3,8010) QSUM*NCH
      WRITE(6,*) ' (NOTE: SEE OUTPUT FILE FOR PRECISE OUTPUT AT EACH',
     1        ' STATION.)'

      STOP
      END




      REAL*8 FUNCTION NUSELT(REb,PR,TW,TB,X,DH,INU)
CC
CC                    FUNCTION NUSELT
CC                    ---------------
CC    THIS FUNCTION COMPUTES THE NUSSELT NUMBER GIVEN BULK FLOW CONDITIONS.
CC
```

```
CC   AUTHOR:     JAMES T. WALTON, NASA LEWIS RESEARCH CENTER
CC   ORIGINATION: SEPTEMBER 16, 1991
CC   LAST MOD.:   NOVEMBER  25, 1991
CC
      IMPLICIT REAL*8 (A-H,O-Z)
      REAL*8 K1,K2,NU0

      IF (INU.EQ.0) GOTO 8000
      GOTO (1,2,3,4,5,6,7,8,9,10), INU
      GOTO 9990

C.....LOCAL NUSSELT NUMBER BASED ON ANALYTICAL SOLUTION.  VALID OVER
C     10000<RE<5000000, .5<PR<2000, WITHIN +-4% FOR H2.
C     (PETUKHOV, B.S.:  HEAT TRANSFER AND FRICTION IN TURBULENT PIPE FLOW.
C      ADVANCES IN HEAT TRANSFER, ACEDEMIC PRESS, NEW YORK, 1970.
    1 IF ((REb.LT.10000.).OR.(REb.GT.5000000.)) WRITE(6,9900) INU,REb
      ET     = (1.82*DLOG10(REb)-1.64)**(-2.)
      K1     = 1.  + 3.4*ET
      K2     = 11.7 + 1.8*PR**(-.33333)
      Nu0    = ET*REb*PR/8./(K1+K2*SQRT(ET/8.)*(PR**(.6667)-1.))
      NUSELT = Nu0*(TW/TB)**(-.31*DLOG10(TW/TB)-.36)
      GOTO 9999

C.....LOCAL NUSSELT NUMBER FOR TURBULENT FLOW IN SMOOTH PIPES DERIVED FROM
C     EXPERIMENTAL DATA FOR HIGH TEMPERATURE HYDROGEN, HELIUM, AND AIR.
C     ACCURATE WITHIN +-10%.
C     (WOLF, H.; McCARTHY, J.R.:  HEAT TRANSFER TO HYDROGEN AND HELIUM WITH
C      WALL TO FLUID TEMPERATURE RATIOS TO 11.09.  ROCK.DYN. RR-60-12, 12/60.
C      REF. BY BUSSARD, R.W.; DELAUER, R.D.:  FUNDEMENTALS OF NUCLEAR FLIGHT.
C      McGRAW-HILL, NEW YORK, 1965.)
    2 IF (REb.LT.2300) WRITE(6,9900) INU,REb
      NUSELT = .045*REb**0.8*PR**0.4*(TW/TB)**(-0.55)*(1.+X/DH)**(-0.15)
      GOTO 9999

C.....LOCAL NUSSELT NUMBER BASED ON MODIFIED McCARTHY-WOLF
C     (REFERENCED IN TRACK II - WANL-TME-2697, MAY 1970.)
    3 IF (REb.LT.1200)
     1 NUSELT = (4.36 + (0.036*REb*PR*DH/X)/(1.+0.001*REb*PR*DH/X))*
     1         (TW/TB)**.25
      IF (REb.LT.1200.) GOTO 9999
      IF ((TW/TB).GT.3.5) WRITE(6,9901) INU,TW/TB
       NUSELT = 0.025*REb**0.8*PR**0.4*(TB/TW)**(0.55)*(1.+.3*
     1         (X/DH)**(-.7))
       GOTO 9999

C.....LOCAL NUSSELT NUMBER FOR TURBULENT FLOW IN PIPES.
C     ACCURATE WITHIN +-10%.
C     (McELIGOT, D.M.; MAGEE, P.M.:  AEROTHERMODYNAMIC STUDIES AT HIGH
C      TEMPERATURE.  STANFORD DEPT OF M.E., NUCLEAR ENGINEERING LABORATORY,
C      TRN 326-1, JUNE 1962.  REF. BY TORY IIC - UCRL-12069)
    4 IF (REb.LT.2300) WRITE(6,9900) INU,REb
      NUSELT = .021*REb**0.8*PR**0.4*(TW/TB)**(-0.47)*(1.+X/DH**(-0.7))
      GOTO 9999

C.....NUSSELT NUMBER FROM WORSOE-SCHMIDT AND PERKINS CORRELATION.  THIS
C     RELATION MAY HAVE BEEN DEVELOPED BASED ON A NITROGEN DATA IN A
C     CONSTANT ELECTRICALLY HEATED INCONEL TUBE WITH AN OVERALL L/D=160.
C     18300<RE<279000, 1.24<TW/TB<7.54.  ACCURACY WITHIN +-20%.
C     (PERKINS, H.C.; WORSOE-SCHMIDT, P.  INTERN. J. HEAT MASS TRANSFER,
C      8, NO. 7, 1011-1031, 1965.  REF. BY PEWEE-1 - LA-4217-MS)
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   5 IF (REb.LT.18300.) WRITE(6,9900) INU,REb
     NUSELT = .024*REb**0.8*PR**0.4*(TW/TB)**(-0.7)*(1.+X/DH**(-0.7)*
    1        (TW/TB)**(.7))
     GOTO 9999

C.....LOCAL NUSSELT NUMBER CORRELATION FOR TURBULENT AND LAMINAR FLOW.
C     THE TURBULENT RELATION IS A MODIFIED DALLE-DONNE CORRELATION DEVELOPED
C     IN HELIUM AND AIR WITH A TUBE 10 < L/D <240, 200 < TIN < 2800 R,
C     1.1 < TW/TB < 8.  THE REYNOLD RANGE IS 30000 < RE < 400,000 WITH
C     64% OF THE DATA WITHIN +-20%.
C      (MILLER, J.V.; TAYLOR, M.F.:  IMPROVED METHOD OF PREDICTING SURFACE
C      TEMPERATURES IN HYDROGEN-COOLED NUCLEAR ROCKET REACTOR AT HIGH
C      SURFACE-TO-BULK-TEMPERATURE RATIOS.  NASA TN D-2594, 1965.
C      KAYS, W.M.:  NUMERICAL SOLUTIONS FOR LAMINAR-FLOW HEAT TRANSFER IN
C      CIRCULAR TUBES.  TRANS. ASME, VOL. 77, NOV. 1955, PP.1265-1274.
C      REF. IN CLARK - NASA TM-X-1232)
   6 IF (REb.LT.2300.)
    1    NUSELT = 4.36 + (0.036*REb*PR*DH/X)/(1.+0.0011*REb*PR*DH/X)
     IF (REb.GE.2300.)
    1    NUSELT = .021*REb**0.8*PR**0.4*(TW/TB)**(-0.29-0.0019*X/DH)
      GOTO 9999

C.....WANL NUSSELT NUMBER CORRELATION WHICH IS A COMBINATION OF THE WORK
C     DONE BY PETUHKOV AND THAT OF McCARTHY-WOLF.
C     (TRACK II - A COMPUTER PROGRAM FOR TRANSIENT THERMAL ANALYSIS OF
C     FLOW SYSTEMS WITH MULTIPLE PARALLEL AND SERIES CHANNELS.  WANL-TME-2697,
C     MAY 1970.)
   7 IF (REb.LT.1200)
    1 NUSELT = (4.36 + (0.036*REb*PR*DH/X)/(1.+0.001*REb*PR*DH/X))*
    1        (TW/TB)**.25
     IF (REb.LT.1200.) GOTO 9999
     PXXX   = 0.11859090909 + 0.007146590909*X/DH - 0.000027083333*
    1                                    X*X/DH/DH
     IF ((X/DH).LT.80.)
    1 NUSELT = 0.0212*REb**.8*PR**.4*(TB/TW)**PXXX
     IF (((X/DH).GE.80.).AND.((X/DH).LE.260.))
    1 NUSELT = (0.0212+0.000211*(X-.2032))*REb**.8*PR**.4*(TB/TW)**.55
     IF ((X/DH).GT.260.)
    1 NUSELT = 0.025*REb**.8*PR**.4*(TB/TW)**.55
     GOTO 9999

C.....LASL NUSSELT NUMBER CORRELATION 73% OF DATA WITHIN +-20%
C      (WILLIAMSON, K.D.; BARTLIT, J.R.; THRUSTON, R.S.:  STUDIES OF FORCED
C       CONVECTION HEAT TRANSFER TO CRYOGENIC FLUIDS.  C.E.P. SYMPOSIUM,
C       SERIES 87, VOL 64, 1968.  REF. IN TRACK II - WANL-TME-2697)
   8 IF (REb.LT.1200)
    1 NUSELT = (4.36 + (0.036*REb*PR*DH/X)/(1.+0.001*REb*PR*DH/X))*
    1        (TW/TB)**.25
     IF (REb.LT.1200.) GOTO 9999
     C1     = 1.
     C2     = 0.765
     IF ((TW/TB).GE.1.8) C1 = 0.7
     IF ((TW/TB).GE.1.8) C2 = 0.2
     NUSELT = 0.023*REb**.8*PR**.4*C1*(TB/TW)**C2
     GOTO 9999

C.....NUSSELT NUMBER CORRELATION FROM TAYLOR EQUATION.
C      (DURHAM, FRANKLIN P.:  NUCLEAR ENGINE DEFINITION STUDY PRELIMINARY
C       REPORT, VOL. II - SUPPORTING STUDIES (SMALL ENGINE).  LA-5044-MS, 9/72)
   9 NUSELT = 0.023*REb**.8*PR**.4*(TW/TB)**(-.57+1.59*DH/X)
```

```
      GOTO 9999

C.....NUSSELT NUMBER CORRELATION FROM EARLY MCCARTHY & WOLF BASED ON H2 IN
C     ELECTRICALLY HEATED STAINLESS STEEL TUBE (L/D = 67 OR 42.6).  GOOD FOR
C     1.5 < TW/TB < 2.8 & 7800 < RE < 1500000.
C     (MCCARTHY, J.R.; WOLF, H.:  FORCED CONVECTION HEAT TRANSFER TO GASEOUS
C      HYDROGEN AT HIGH HEAT FLUX AND HIGH PRESSURE IN A SMOOTH, ROUND,
C      ELECTRICALLY HEATED TUBE.  ARS JOURNAL, P.423-425, APRIL 1960.
   10 IF (REb.LT.7800.) WRITE(6,9900) INU,REb
      NUSELT = 0.023*REb**.8*PR**.4*(TW/TB)**(-.3)
      GOTO 9999


C.....
 8000 WRITE(6,8001)
 8001 FORMAT(/./././././././././././././././././././././././././././././.
     1 '                SELECT NUSSELT NUMBER CORRELATION',/,
     2 '                ------------------------------',/,/,
     212X,'(1) PETUKHOV ANALYTICAL SOLUTION (+-4%)',/,
     312X,'(2) WOLF-McCARTHY RELATION (I) FOR SMOOTH CHANNELS (+-10%)',/,
     412X,'(3) WANL TRACK II CORRELATION FOR SMOOTH CHANNELS',/,
     512X,'(4) McELIGOT-MAGEE RELATION BASED ON AIR DATA',/,
     612X,'(5) WORSOE-SCHMIDT RELATION BASED ON N2 DATA',/,
     712X,'(6) MODIFIED DALLE-DONNE CORRELATION BASED ON HE & AIR',/,
     812X,'(7) WANL RELATION FROM PETUHKOV & McCARTHY-WOLF',/,
     910X,'* (8) LASL RELATION FROM WILLIAMSON-BARTLIT-THRUSTON',/,
     O12X,'(9) TAYLOR EQUATION USED IN SMALL ENGINE DESIGN EFFORT',/,
     111X,'(10) WOLF-McCARTHY RELATION (II) FOR SMOOTH CHANNELS',/,
     1 /./././././.'                          ENTER NUMBER: ')
      READ(5,*) NUSELT
      WRITE(6,8002)
 8002 FORMAT(/./././././././././././././././././././././././././././././././)
      WRITE(3,8003) NUSELT
 8003 FORMAT(' NUSSELT NUMBER CORRELATION #',F2.0)
      GOTO 9999


 9900 FORMAT(' REYNOLDS NUMBER OUT OF SCOPE OF NUSSELT NUMBER',
     1 'CORRELATION #',I2,/,' (CURRENT REb=',F10.1,')')
 9901 FORMAT(' TW/TB OUT OF SCOPE OF NUSSELT NUMBER ',
     1 ' CORRELATION #',I2,/,' (CURRENT TW/TB=',F10.2,')')
 9902 FORMAT(' STOP ---- FUNCTION NUSELT COMPUTED  NU < 0')

 9990 WRITE(6,*) ' ERROR - INCORRECT VALUE FOR INU DETECTED IN',
     1         ' FUNCTION NUSELT'
      STOP
 9999 IF (NUSELT.LE.0.) WRITE(6,9902)
      IF (NUSELT.LE.0.) STOP
      RETURN
      END




      REAL*8 FUNCTION CFRICT(REb,TW,TB,DH,EROUGH,PB,WCH,ICF)
CC
CC                      FUNCTION CFRICT
CC                      ---------------
CC    THIS FUNCTION COMPUTES THE FRICTION FACTOR GIVEN BULK FLOW CONDITIONS.
CC
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CC   AUTHOR:     JAMES T. WALTON,  NASA LEWIS RESEARCH CENTER
CC   ORIGINATION: SEPTEMBER 17, 1991
CC   LAST MOD.:   NOVEMBER  25, 1991
CC
     IMPLICIT REAL*8 (A-H,O-Z)

     IDUM  = -1

     IF (ICF.EQ.0) GOTO 8000
     GOTO (1,2,3,4,5,6,7,8,9,10), ICF
     GOTO 9990

C    FRICTION FACTOR FROM ANALYTICAL SOLUTION.
C    (PETUKHOV, B.S.:  HEAT TRANSFER AND FRICTION IN TURBULENT PIPE FLOW.
C     ADVANCES IN HEAT TRANSFER, ACEDEMIC PRESS, NEW YORK, 1970.
   1 ET    = (1.82*DLOG10(REb)-1.64)**(-2.)
     IDUM  = 0
     CALL PH2(DUM,PB,TW,DUM1,VISW,DUM2,DUM3,DUM4,DUM5,DUM6,IDUM)
     REw   = 4.*WCH/3.14159/DH/VISw*(TB/TW)**2
     CFRICT = ET*(TW/TB)**(-.6+5.6*REw**(-.38))
     GOTO 9999


C.....FRICTION FACTOR CORRELATION FOR GRAPH-I-TITE G FUEL ELEMENTS AS
C    DETERMINED BY AEROJET-GENERAL CORP. FOR A ROUGHNESS OF 0.006 AND
C    FOR 2300<RE<100,000.
C    (ANON.: COLD FLOW TEST OF REACTOR CLUSTER AND SUBSTITUTE REACTOR
C     CLUSTER.  AGC RN-S-0058.  REF BY CLARK NASA TMX).
   2 IF (REb.GT.120000) WRITE(6,9900) ICF,REb
     IF (REb.LT.2300) CFRICT = 16./REb
     IF (REb.GE.2300) CFRICT = .25*(0.0345+363/REb**1.25)
     GOTO 9999

C.....FRICTION FACTOR CORRELATION FOR SMOOTH TUBES.
C    (BUSSARD, R.W.; DELAUER, R.D.:  NUCLEAR ROCKET PROPULSION.  MCGRAW-
C     HILL, NEW YORK, 1958.)
   3 IF (REb.GT.200000.) WRITE(6,9900) ICF,REb
     IF (REb.LT.5000) CFRICT = 16./REb
     IF (REb.GE.5000) CFRICT = 0.046/REb**.2
     GOTO 9999

C.....FRICTION FACTOR FROM MOODY
C    (ANON.: PEWEE-1 REACTOR TEST REPORT.  LA-4217-MS, AUGUST 1969)
   4 IDUM  = 0
     TENG  = (TW+TB)/2
     CALL PH2(DUM1,PB,TENG,DUM2,VISf,DUM3,DUM4,DUM5,DUM6,DUM7,IDUM)
     REf   = 4.*WCH/3.14159/DH/VISf
     CFRICT = 0.0055*(1.+(20.*EROUGH+1000000./REf)**.333333333)
     GOTO 9999

C.....FRICTION FACTOR FROM 710 PROGRAM CORRECTED FOR ROUGHNESS
C    (ANON.:  QUARTERLY PROGRESS REPORT (710 PROGRAM) NO. 1.  GEMP-210,
C     MAY 1963.
   5 CFRICT = 1.35*(0.046/REb**.2)
     GOTO 9999

C.....KOO EQUATION FRICTION FACTOR FOR SMOOTH TUBE.
C    (McADAMS, W.H.: HEAT TRANSMISSION.  THIRD ED., MCGRAW-HILL, 1958.
C     REF BY CLARK NASA TMX-1232)
   6 IF (REb.LT.2300) CFRICT = 16./REb
```

```
      IF (REb.GE.2300) CFRICT = 0.0014 + 0.125/REb**.32
      GOTO 9999

C.....FRICTION FACTOR FOR TUBE WITH RELATIVE ROUGHNESS OF 0.006 DEVELOPED
C     FROM MOODY DIAGRAM.
C     (CLARK, J.S.: COMPARISON OF PREDICTED AND EXPERIMENTAL OPERATING
C      CHARACTERISTICS OF A NUCLEAR-ROCKET-CORE. NASA TM-X-1232, 1965.
    7 IF (REb.LT.2300) CFRICT = 16./REb
      IF (REb.GE.2300) CFRICT = 0.25*(0.03172+7.2/REb**.75)
      GOTO 9999

C     TAYLOR CORRELATION FOR FRICTION FACTOR IN A SMOOTH TUBE DEVELOPED FOR
C     H2, AIR, N2, HE AND GOOD FOR +-10% OVER 3000 < RE < 187000.
C     (TAYLOR, M.F.: A METHOD OF CORRELATING LOCAL AND AVERAGE FRICTION
C      COEFFICIENTS FOR BOTH LAMINAR AND TURBULENT FLOW OF GASES THROUGH
C      A SMOOTH TUBE. INTL HEAT AND MASS TRANSFER SHORTER COMMUNICATIONS,
C      AUGUST 1967 (67A36941). REF BY TRACK II WANL-TME-2697.
    8 IDUM  = 0
      CALL PH2(DUM,PB,TW,DUM1,VISW,DUM2,DUM3,DUM4,DUM5,DUM6,IDUM)
      REw   = 4.*WCH/3.14159/DH/VISw*TB/TW
      IF (REw.LT.1070) CFRICT = 16./REw
      IF (REw.LT.1070) GOTO 9999
      CFRICT = (0.0014+0.125/REw**.32)*SQRT(TB/TW)
      GOTO 9999

C     THE FRICTION FACTOR CORRELATION USED IN TNT-II CALCULATIONS FOR
C     ROUGH SURFACE.
C     (ANON.: THERMAL AND FLUID FLOW ANALYSIS WANL TME-2753)
    9     IDUM  = 0
      CALL PH2(DUM,PB,TW,DUM1,VISW,DUM2,DUM3,DUM4,DUM5,DUM6,IDUM)
      REw   = 4.*WCH/3.14159/DH/VISw*TB/TW
      IF (REw.LT.2000) CFRICT = 16./REw
      IF (REw.LT.2000) GOTO 9999
      A     = 495./EROUGH**1.138
      FA    = 0.0014 + .125/A**.32
      FB    = 0.0014 + .125/(A/20.)**.32
      REw1  = REw
      IF (REw.GT.A) REw1 = A
      P     = REw1/A
      Q     = .3 - .1*P
      Y     = (FB-FA)*P**Q
      F1    = SQRT((0.0014+.125/REw**.32)*SQRT(TB/TW)+Y)
      FT    = (2.28+4.*DLOG10((EROUGH+4.675/REw/F1)**(-1)))**(-2.)
      IF ((REw.GT.2000.).AND.(REw.LT.3000.))
     1 CFRICT = FT*(REW-2000)/1000. + 16./REW*(1.-(REW-2000.)/1000.)
      IF (REw.GE.3000.) CFRICT = FT
      GOTO 9999

C.....FRICTION FACTOR FOR TUBE WITH RELATIVE ROUGHNESS OF 0.004 DEVELOPED
C     FROM MOODY DIAGRAM.
C     (CLARK, J.S.: ANALYTICAL AND EXPERIMENTAL STUDY OF STARTUP CHARAC.
C      OF A FULL-SCALE UNFUELED NUCLEAR ROCKET CORE ASSEMBLY.
C      NASA TM-X-1231, 1965.
   10 IF (REb.LT.2300) CFRICT = 16./REb
      YX    = DLOG(REb*10E-06)+10.
      IF (REb.GE.2300) CFRICT = (0.1552-0.04412*YX+0.005318*YX*YX-
     1              0.0002881*YX*YX*YX+0.000005903*YX*YX*YX*YX)/4.
      GOTO 9999

C.....
```

```
8000 WRITE(6,8001)
8001 FORMAT(/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,
   1 '                  SELECT FRICTION FACTOR CORRELATION',/,
   2 '                  ----------------------------------',/,/,
   212X,'(1) PETUKHOV ANALYTICAL SOLUTION',/,
   310X,'* (2) GRAPH-I-TITE G FUEL ELEMENT FRICTION RELATION ',/,
   412X,'(3) BASIC FRICTION FOR LAMINAR AND TURBULENT (e=0) ',/,
   512X,'(4) MOODY BASED FRICTION FACTOR (e=INPUT VALUE)',/,
   612X,'(5) BASIC FRICTION FOR TURBULENT * 1.35 CORRECTION',/,
   712X,'(6) KOO EQUATION FOR SMOOTH TUBES                  ',/,
   812X,'(7) RELATION FROM MOODY DIAGRAM FOR e=0.006    ',/,
   912X,'(8) TAYLOR RELATION FOR FRICTION FACTOR (e=0)  ',/,
   O10X,'* (9) TAYLOR RELATION FOR FRICTION FACTOR (e=INPUT VALUE)',/,
   O11X,'(10) RELATION FROM MOODY DIAGRAM FOR e=0.004   ',/,
   1 /,/,/,/,/,/,'                        ENTER NUMBER: ')
    READ(5,*) CFRICT
    WRITE(6,8002)
8002 FORMAT(/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/)
    WRITE(3,8003) CFRICT
8003 FORMAT(' FRICTION FACTOR CORRELATION #',F2.0)
    GOTO 9999

9900 FORMAT(' REYNOLDS NUMBER OUT OF SCOPE OF FRICTION FACTOR',
   1 'CORRELATION #',I2,/,' (CURRENT REb=',F10.1,')')
9901 FORMAT(' STOP ---- FUNCTION CFRICT COMPUTED f <= 0')

9990 WRITE(6,*) ' ERROR - INCORRECT VALUE FOR ICF DETECTED IN',
   1         ' FUNCTION CFRICT'
    STOP
9999 IF (CFRICT.LE.0.) WRITE(6,9901)
    IF (CFRICT.LE.0.) STOP
    RETURN
    END


    REAL*8 FUNCTION PSFCAL(XOL,IPSF)
CC
CC                    FUNCTION PSFCAL
CC                    ---------------
CC   THIS FUNCTION COMPUTES THE POWER SHAPE FACTOR GIVEN AXIAL POSITION.
CC
CC   AUTHOR:      JAMES T. WALTON,  NASA LEWIS RESEARCH CENTER
CC   ORIGINATION: SEPTEMBER 19, 1991
CC   LAST MOD.:   NOVEMBER  25, 1991
CC
    IMPLICIT REAL*8 (A-H,O-Z)


    IF (IPSF.EQ.0) GOTO 8000
    GOTO (1,2,3,4,5,6,7,8), IPSF
    GOTO 9990

C.....POWER SHAPING FACTOR COEFFICIENTS FOR CURVE USED BY TNT-II PROGRAM.
C    (NERVA ENGINE DATA AND DESIGN CONCEPTS, VOL. III - THERMAL AND FLUID
C     FLOW ANALYSIS.  WANL-TME-1798, JUNE 1968.)
   1 A     = 0.240243623548
     B     = 3.18743980258
     C     = 1.14783695957
     D     =-7.52353879018
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      E     = 3.23771164993
      GOTO 9999

C.....POWER SHAPE FACTOR COEFFICIENTS FOR CURVE OF NRX-A2 REACTOR.
C     (NRX-A2 TEST FINAL REPORT.  WANL-TNR-193, MARCH 1965.)
    2 A     = 0.360742338891
      B     = 4.50215211498
      C     =-4.94032044875
      D     =-0.481081746774
      E     = 0.768777777651
      GOTO 9999

C.....POWER SHAPE FACTOR COEFFICIENTS FOR CURVE OF NRX-A3 REACTOR.
C     (NRX-A5 REACTOR TEST ANALYSIS REPORT.  WANL-TNR-219, MARCH 1967.)
    3 A     = 0.388914519476
      B     = 4.02639441610
      C     =-3.35296846791
      D     =-2.71711572027
      E     = 1.95396600540
      GOTO 9999

C.....POWER SHAPE FACTOR COEFFICIENTS FOR CURVE OF NRX-A4/EST REACTOR.
C     (NRX-A5 REACTOR TEST ANALYSIS REPORT.  WANL-TNR-219, MARCH 1967.)
    4 A     = 0.523554259920
      B     = 3.11216568076
      C     = 0.429960285933
      D     =-9.51785121938
      E     = 5.82723420430
      GOTO 9999

C.....POWER SHAPE FACTOR COEFFICIENTS FOR CURVE OF NRX-A5 REACTOR.
C     (NRX-A5 REACTOR TEST ANALYSIS REPORT.  WANL-TNR-219, MARCH 1967.)
    5 A     = 0.203569633244
      B     = 5.59270800308
      C     =-7.77244060348
      D     = 2.39244292069
      E     =-0.0106892741948
      GOTO 9999

C.....POWER SHAPE FACTOR COEFFICIENTS FOR CURVE OF NRX-A6 REACTOR.
C     (NRX-A6 REACTOR TEST ANALYSIS REPORT.  WANL-TNR-223, AUGUST 1968.)
    6 A     = 0.342910797012
      B     = 3.85198430654
      C     =-0.721844448175
      D     =-8.27798616356
      E     = 5.09908210847
      GOTO 9999


C.....POWER SHAPE FACTOR COEFFICIENTS FOR CURVE OF PEWEE-1 REACTOR.
C     (PEWEE-1 REACTOR TEST REPORT.  LA-4217-MS, JUNE 1969.)
    7 A     = 0.315263743551
      B     = 4.01075764283
      C     =-2.81198488737
      D     =-2.13642616902
      E     = 0.653731955838
      GOTO 9999

C.....POWER SHAPE FACTOR COEFFICIENTS FOR CURVE OF SMALL ENGINE REACTOR.
C     (DURHAM, FRANKLIN P.:  ENGINE DEFINITION STUDY.  LA-5044-MS, VOL. I-III,
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C     SEPTEMBER 1972.)
   8 A     = 0.370101535438
     B     = 4.33086012101
     C     =-4.51483233018
     D     =-0.0955935232165
     E     = 0.0959623283744
     GOTO 9999

C.....
 8000 WRITE(6,8001)
 8001 FORMAT(/././././././././././././././././././././././././././././.
    1 '                SELECT AXIAL POWER SHAPE CORRELATION',/,
    2 '                ------------------------------------',/,/,
    212X,'(1) PROGRAM TNT-II NERVA MODEL CIRCA 1968',/,
    412X,'(2) NRX-A2 REACTOR MODEL BASED ON EXPERIMENTAL DATA',/,
    412X,'(3) NRX-A3 REACTOR MODEL BASED ON EXPERIMENTAL DATA',/,
    412X,'(4) NRX-A4/EST REACTOR MODEL BASED ON EXPERIMENTAL DATA',/,
    412X,'(5) NRX-A5 REACTOR MODEL BASED ON EXPERIMENTAL DATA',/,
    412X,'(6) NRX-A6 REACTOR MODEL BASED ON EXPERIMENTAL DATA',/,
    312X,'(7) PEWEE-1 REACTOR MODEL                    ',/,
    912X,'(8) SMALL ENGINE REACTOR MODEL                 ',/,
    O12X,'                                          ',/,
    1 /./././././.'                       ENTER NUMBER: ')
     READ(5,*) PSFCAL
     WRITE(6,8002)
 8002 FORMAT(/././././././././././././././././././././././././././././././)
     WRITE(3,8003) PSFCAL
 8003 FORMAT(' POWER SHAPE FACTOR CORRELATION #',F2.0)
     RETURN


 9901 FORMAT(' STOP ---- FUNCTION PSFCAL COMPUTED PSF <= 0')
 9990 WRITE(6,*) ' ERROR - INCORRECT VALUE FOR IPSF DETECTED IN',
    1         ' FUNCTION PSFCAL'
     STOP

 9999 PSFCAL = A + B*XOL + C*XOL*XOL + D*XOL*XOL*XOL + E*XOL*XOL*XOL*XOL
     IF (PSFCAL.LE.0.) WRITE(6,9901)
     IF (PSFCAL.LE.0.) STOP
     RETURN
     END



     SUBROUTINE BANNER(VERSION,DATE)
CC                    SUBROUTINE BANNER
CC                    ----------------
CC
CC   THIS SUBROUTINE WRITES THE STANDARD NASA PROGRAM BANNER PAGE
CC   TO THE TERMINAL SCREEN.
CC
CC   AUTHOR:          JAMES T. WALTON, NASA LEWIS RESEARCH CENTER
CC   ORIGINATION:      MAY  13, 1991
CC   LAST MODIFICATION: SEPTEMBER 17, 1991
CC
     IMPLICIT REAL*8 (A-H,O-Z)
     CHARACTER JUNK*12,DATE*20,FILEINP*12,FILEOUT*12
     DATA FILEINP/'ELM.INP'/,FILEOUT/'ELM.OUT'/

     WRITE(6,10) VERSION, DATE
```

```
 10 FORMAT(/,/,/,/,/,/,/,/,
  1 17X,'NATIONAL AERONAUTICS AND SPACE ADMINISTRATION',/,
  2 29X,'LEWIS RESEARCH CENTER',/,
  3 32X,'CLEVELAND, OHIO',/,/,/,
  4 16X,'                PROGRAM ELM',/,
  4 16X,'                 LEW-15423',/,
  4 17X,'  NUCLEAR ROCKET ENGINE FUEL ELEMENT ANALYSIS  ',/,/,/,
  5 34X,'VERSION ',F4.2,/,/,/,/,/,15X,
  6' AUTHOR: JAMES T. WALTON, NASA LEWIS RESEARCH CENTER',/,/,
  7 26X,'ORIGINATION:  SEPTEMBER 12, 1991',/,
  8 26X,'VERSION DATE: ',A20,/,/,/,/,/,
  9 26X,'STRIKE <ENTER> TO CONTINUE....')
    READ(5,20) JUNK
 20 FORMAT(A12)
    WRITE(6,30)
 30 FORMAT(/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/,/)
    WRITE(6,*) ' ENTER INPUT FILE NAME (DEFAULT=',FILEINP,'): '
    READ(5,20) JUNK
    IF (JUNK.NE.' ') FILEINP = JUNK
    WRITE(6,*) ' ENTER OUTPUT FILE NAME (DEFAULT=',FILEOUT,'): '
    READ(5,20) JUNK
    IF (JUNK.NE.' ') FILEOUT = JUNK

    OPEN (UNIT=2,FILE=FILEINP,STATUS='OLD')
    OPEN (UNIT=3,FILE=FILEOUT,STATUS='UNKNOWN')
    RETURN
    END


    SUBROUTINE READER(TIN,PIN,DH,POWER,NCH,WCH,L,DL,EROUGH,CLIN,CLOUT,
   1              DFE,DORF)
CC                      SUBROUTINE READER
CC                      ----------------
CC
CC   THIS SUBROUTINE PERFORMS ALL READS FROM THE INPUT FILE.
CC
CC   AUTHOR:          JAMES T. WALTON, NASA LEWIS RESEARCH CENTER
CC   ORIGINATION:     JUNE 14, 1991
CC   LAST MODIFICATION:FEBRUARY 20, 1991
CC
     IMPLICIT REAL*8 (A-H,O-Z)
     REAL*8 NCH,L
     CHARACTER*65 JUNK,ACARD

     READ(2,1) JUNK
     READ(2,1) ACARD
     WRITE(3,1) ACARD
     READ(2,1) JUNK
     READ(2,1) JUNK
     READ(2,1) JUNK,POWER
     WRITE(3,1) JUNK,POWER
     READ(2,1) JUNK,PIN
     WRITE(3,1) JUNK,PIN
     READ(2,1) JUNK,TIN
     WRITE(3,1) JUNK,TIN
     READ(2,1) JUNK,WCH
     WRITE(3,1) JUNK,WCH
     READ(2,1) JUNK,DH
     WRITE(3,1) JUNK,DH
     READ(2,1) JUNK,NCH
```

```
      WRITE(3,1) JUNK,NCH
      READ(2,1) JUNK,L
      WRITE(3,1) JUNK,L
      READ(2,1) JUNK,DL
      WRITE(3,1) JUNK,DL
      READ(2,1) JUNK,EROUGH
      WRITE(3,1) JUNK,EROUGH
      READ(2,1) JUNK,CLIN
      WRITE(3,1) JUNK,CLIN
      READ(2,1) JUNK,CLOUT
      WRITE(3,1) JUNK,CLOUT
      READ(2,1) JUNK,DFE
      WRITE(3,1) JUNK,DFE
      READ(2,1) JUNK,DORF
      WRITE(3,1) JUNK,DORF
      WRITE(3,*)
      WRITE(3,*)

    1 FORMAT(A65,E14.6)
      RETURN
      END


C.....MODIFICATIONS
C.....VERSION 1.00 ---> 1.01
C  1) CORRECTED NEWTONS LAW OF COOLING TO USE ADIABATIC WALL TEMPERATURE.
C
C.....VERSION 1.01 ---> 1.02
C  1) CONVERTED TOUT CALCULATION FROM Q = M*CP*(TOUT-TIN) TO HTOUT=HTIN+Q
C  2) ACCOUNT FOR ENTRANCE AND EXIT LOSSES
C
C.....VERSION 1.02 ---> 1.03
C  1) UPDATE HYDROGEN PROPERTIES MODEL TO NBS STANDARD LEW-15505
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TABLE I.—POWER SHAPE FACTOR CORRELATION COEFFICIENTS

Regression Model Name	A	B	C	D	E
NRX Model	.240243623548	.18743980258	1.14783695957	-7.52353879018	3.23771164993
NRX-A2 Model	.360742338891	4.50215211498	-4.94032044875	-0.481081746774	.768777777651
NRX-A3 Model	.388914519476	4.02639441610	-3.35296846791	-2.71711572027	1.95396600540
NRX-A4 Model	.523554259920	3.11216568076	.429960285933	-9.51785121938	5.82723420430
NRX-A5 Model	.203569633244	5.59270800308	-7.77244060348	2.39244292069	-.010689274194
NRX-A6 Model	.342910797012	3.85198430654	-.721844448175	-8.27798616356	5.09908210847
PEWEE-1 Model	.315263743551	4.01075764283	-2.81198488737	-2.13642616902	.653731955838
SMALL ENGINE Model	.370101535438	4.33086012101	-4.51483233018	-.0955935232165	.0959623283744

TABLE II.—INPUT DATA FILE FOR NRX-A3 REACTOR EXPERIMENT

POWER	. . . the total thermal power generated/fuel element (W)	621500.
PIN	. . . the fuel element inlet stagnation pressure (psi)	687.
TIN	. . . the fuel element inlet static temperature (R)	221.
WCH	. . . the fuel element mass flow rate (lb/s)	0.04267
DH	. . . the coolant channel hydraulic diameter (in)	0.091
NCH	. . . the number of coolant channels/fuel element	19.
L	. . . the length of the fuel element (in)	52.
DL	. . . the computational step size (in)	2.
EROUGH	. . . the surface roughness, required by some f models (in)	0.008
CLIN	. . . the entrance loss coefficient (1.28<CL<1.75)	−1.
CLOUT	. . . the exit loss coefficient	−1.
DFE	. . . the distance across element flats (in)	0.75
DORF	. . . the inlet orifice diameter (in)	0.

TABLE III.–PROGRAM ELM OUTPUT FILE FOR NRX–A3 REACTOR EXPERIMENT

PROGRAM ELM
VERSION 1.02
FEBRUARY 26, 1992

NRX-A3 EXPERIMENT CRT 21550

X (in.)	Tb (R)	Tw (R)	Cum. P(W)	Re	Pb (psi)	MACH
00.00	0221.00	0221.00	00000.00	000000.	686.39	0.000
02.00	0283.58	0670.73	00585.12	100327.	685.69	0.034
04.00	0365.16	0922.04	01351.99	085798.	685.70	0.039
06.00	0469.47	1181.51	02286.53	073070.	684.81	0.044
08.00	0597.50	1422.34	03373.76	062331.	683.40	0.050
10.00	0744.51	1635.95	04597.91	053635.	681.68	0.055
12.00	0907.27	1838.77	05942.56	046756.	679.63	0.061
14.00	1082.71	2036.56	07390.80	041311.	677.25	0.067
16.00	1268.13	2231.18	08925.28	036968.	674.51	0.073
18.00	1460.66	2421.42	10528.42	033469.	671.40	0.079
20.00	1657.58	2606.67	12182.49	030623.	667.93	0.085
22.00	1856.34	2785.60	13869.76	028287.	664.09	0.091
24.00	2054.49	2956.63	15572.63	026353.	659.88	0.097
26.00	2249.76	3118.07	17273.74	024740.	655.30	0.102
28.00	2440.04	3268.92	18956.13	023386.	650.36	0.108
30.00	2623.45	3408.46	20603.33	022244.	645.06	0.113
32.00	2801.57	3538.26	22199.53	021117.	639.49	0.118
34.00	2967.49	3657.16	23729.69	020261.	633.54	0.123
36.00	3123.22	3762.09	25179.63	019534.	627.27	0.128
38.00	3269.06	3851.41	26536.26	018909.	620.68	0.132
40.00	3400.35	3923.59	27787.60	018376.	613.80	0.137
42.00	3517.64	3979.80	28922.98	017929.	606.66	0.141
44.00	3620.45	4021.05	29933.12	017555.	599.27	0.146
46.00	3708.47	4047.58	30810.32	017245.	591.65	0.150
48.00	3781.58	4059.59	31548.52	016995.	583.83	0.154
50.00	3839.77	4057.55	32143.48	016797.	575.82	0.157
52.00	3883.21	4050.86	32592.90	016648.	563.98	0.161
			619265.1 = POWER/ELEMENT			

TABLE IV.—INPUT DATA FILE FOR NRX-A4 REACTOR EXPERIMENT

POWER	. . . the total thermal power generated/fuel element (W)	705000.
PIN	. . . the fuel element inlet stagnation pressure (psi)	678.
TIN	. . . the fuel element inlet static temperature (R)	229.
WCH	. . . the fuel element mass flow rate (lb/s)	0.04273
DH	. . . the coolant channel hydraulic diameter (in)	0.095
NCH	. . . the number of coolant channels/fuel element	19.
L	. . . the length of the fuel element (in)	52.
DL	. . . the computational step size (in)	2.
EROUGH	. . . the surface roughness, required by some f models (in)	0.008
6CLIN	. . . the entrance loss coefficient (1.28<CL<1.75)	−1.
CLOUT	. . . the exit loss coefficient	−1.
DFE	. . . the distance across element flats (in)	0.75
DORF	. . . the inlet orifice diameter (in)	0.

TABLE V.—PROGRAM ELM OUTPUT FILE FOR NRX-A4 REACTOR EXPERIMENT

PROGRAM ELM
VERSION 1.02
FEBRUARY 26, 1992

NRX-A4/EST EXPERIMENT CRT 21550

X (In.)	Tb (R)	Tw (R)	Cum. P(W)	Re	Pb (psi)	MACH
00.00	0229.00	0229.00	00000.00	00000.	677.47	0.000
02.00	0317.38	0912.12	00832.72	91683.	676.76	0.033
04.00	0426.31	1210.86	01835.66	75491.	676.77	0.039
06.00	0561.78	1491.09	03004.21	62863.	675.87	0.044
08.00	0720.39	1738.90	04329.99	53022.	674.44	0.050
10.00	0898.22	1969.69	05801.30	45461.	672.71	0.056
12.00	1092.08	2195.72	07403.55	39625.	670.67	0.063
14.00	1299.12	2418.78	09119.69	35062.	668.30	0.069
16.00	1515.99	2637.79	10930.66	31446.	665.59	0.075
18.00	1739.42	2851.00	12815.82	28546.	662.54	0.081
20.00	1966.16	3056.23	14753.38	26196.	659.14	0.087
22.00	2193.00	3251.26	16720.85	24273.	655.39	0.093
24.00	2416.88	3434.22	18695.48	22687.	651.31	0.098
26.00	2635.02	3587.03	20654.67	21370.	646.89	0.104
28.00	2848.34	3746.37	22576.44	20111.	642.21	0.109
30.00	3049.62	3911.17	24439.83	19148.	637.16	0.114
32.00	3240.93	4041.51	26225.37	18335.	631.81	0.118
34.00	3419.98	4152.18	27915.52	17642.	626.17	0.123
36.00	3582.47	4244.44	29495.07	17058.	620.26	0.128
38.00	3729.21	4320.55	30951.59	16569.	614.10	0.133
40.00	3859.91	4381.75	32275.91	16159.	607.71	0.137
42.00	3974.64	4433.05	33462.49	15816.	601.10	0.141
44.00	4075.10	4474.12	34509.89	15530.	594.30	0.145
46.00	4161.55	4503.58	35421.23	15292.	587.30	0.148
48.00	4234.79	4526.33	36204.58	15095.	580.12	0.152
50.00	4296.44	4545.67	36873.42	14934.	572.78	0.155
52.00	4348.60	4559.58	37447.08	14801.	561.58	0.158
			711494.4 = POWER/ELEMENT			

TABLE VI.—INPUT DATA FILE FOR NRX-A5 REACTOR EXPERIMENT

POWER	. . . the total thermal power generated/fuel element (W)	678000.
PIN	. . . the fuel element inlet stagnation pressure (psi)	675.
TIN	. . . the fuel element inlet static temperature (R)	242.
WCH	. . . the fuel element mass flow rate (lb/s)	0.041968
DH	. . . the coolant channel hydraulic diameter (in)	0.093
NCH	. . . the number of coolant channels/fuel element	19.
L	. . . the length of the fuel element (in)	52.
DL	. . . the computational step size (in)	2.
EROUGH	. . . the surface roughness, required by some f models (in)	0.008
CLIN	. . . the entrance loss coefficient (1.28<CL<1.75)	−1.
CLOUT	. . . the exit loss coefficient	−1.
DFE	. . . the distance across element flats (in)	0.75
DORF	. . . the inlet orifice diameter (in)	0.

TABLE VII.—PROGRAM ELM OUTPUT FILE FOR NRX-A5 REACTOR EXPERIMENT

PROGRAM ELM
VERSION 1.02
FEBRUARY 26, 1992

NRX-A5 EXPERIMENT

X (in.)	Tb (R)	Tw (R)	Cum. P(W)	Re	Pb (psi)	MACH
00.00	0242.00	0242.00	00000.00	00000.	674.40	0.000
02.00	0287.67	0597.76	00423.08	93789.	673.83	0.034
04.00	0362.02	0901.02	01110.44	82539.	673.84	0.038
06.00	0466.47	1225.86	02032.18	70681.	673.07	0.042
08.00	0601.45	1523.69	03159.56	59965.	671.79	0.047
10.00	0760.99	1776.83	04464.92	51114.	670.19	0.053
12.00	0940.37	2007.85	05921.74	44128.	668.28	0.060
14.00	1135.29	2226.86	07504.63	38660.	666.02	0.066
16.00	1341.96	2438.42	09189.27	34358.	663.41	0.072
18.00	1556.53	2644.02	10952.51	30942.	660.45	0.078
20.00	1775.64	2843.52	12772.28	28200.	657.12	0.084
22.00	1996.21	3035.74	14627.63	25976.	653.43	0.090
24.00	2215.40	3219.32	16498.73	24153.	649.38	0.096
26.00	2430.69	3392.80	18366.86	22645.	644.98	0.102
28.00	2639.89	3540.05	20214.41	21389.	640.22	0.108
30.00	2844.50	3695.57	22024.88	20175.	635.19	0.113
32.00	3037.85	3857.72	23782.89	19246.	629.77	0.118
34.00	3221.77	3989.71	25474.15	18457.	624.03	0.123
36.00	3395.93	4105.09	27085.49	17778.	617.96	0.128
38.00	3555.47	4204.01	28604.86	17199.	611.60	0.132
40.00	3701.20	4287.95	30021.29	16708.	604.95	0.137
42.00	3832.61	4357.13	31324.95	16292.	598.03	0.142
44.00	3949.37	4414.70	32507.07	15940.	590.86	0.146
46.00	4052.09	4458.92	33560.03	15644.	583.46	0.150
48.00	4140.81	4486.86	34477.29	15397.	575.83	0.154
50.00	4214.77	4500.50	35253.42	15195.	567.99	0.158
52.00	4273.99	4505.38	35884.09	15034.	556.23	0.162
			681797.8 = POWER/ELEMENT			

TABLE VIII.—INPUT DATA FILE FOR NRX-A6 REACTOR EXPERIMENT

POWER	.....the total thermal power generated/fuel element (W)	710000.
PIN	.....the fuel element inlet stagnation pressure (psi)	706.
TIN	.....the fuel element inlet static temperature (R)	222.
WCH	.....the fuel element mass flow rate (lb/s)	0.04141
DH	.....the coolant channel hydraulic diameter (in)	0.092
NCH	.....the number of coolant channels/fuel element	19.
L	.....the length of the fuel element (in)	52.
DL	.....the computational step size (in)	2.
EROUGH	.....the surface roughness, required by some f models (in)	0.008
CLIN	.....the entrance loss coefficient (1.28<CL<1.75)	−1.
CLOUT	.....the exit loss coefficient	−1.
DFE	.....the distance across element flats (in)	0.75
DORF	.....the inlet orifice diameter (in)	0.

TABLE IX.—PROGRAM ELM OUTPUT FILE FOR NRX-A6 REACTOR EXPERIMENT

PROGRAM ELM
VERSION 1.02
FEBRUARY 26, 1992

NRX-A6 EXPERIMENT

X (in.)	Tb (R)	Tw (R)	Cum. P(W)	Re	Pb (psi)	MACH
00.00	0222.00	0222.00	00000.00	00000.	705.49	0.000
02.00	0287.86	0717.10	00598.85	94541.	704.90	0.031
04.00	0376.49	1017.46	01405.44	80193.	704.90	0.036
06.00	0493.31	1329.37	02411.07	67533.	704.13	0.041
08.00	0639.13	1614.93	03603.77	56914.	702.85	0.046
10.00	0808.62	1868.33	04968.63	48436.	701.28	0.052
12.00	0998.33	2109.62	06488.23	41823.	699.38	0.058
14.00	1204.73	2345.13	08143.03	36654.	697.16	0.064
16.00	1424.11	2574.82	09911.72	32580.	694.58	0.070
18.00	1652.62	2798.57	11771.61	29338.	691.65	0.076
20.00	1886.55	3014.51	13699.06	26732.	688.36	0.082
22.00	2122.26	3220.42	15669.82	24618.	684.71	0.088
24.00	2356.27	3414.28	17659.41	22887.	680.70	0.094
26.00	2585.35	3594.84	19643.55	21461.	676.35	0.099
28.00	2810.11	3764.00	21598.50	20269.	671.71	0.105
30.00	3022.69	3921.06	23501.45	19098.	666.71	0.109
32.00	3224.59	4060.62	25330.96	18235.	661.38	0.114
34.00	3414.64	4179.17	27067.25	17503.	655.74	0.119
36.00	3587.31	4277.45	28692.68	16888.	649.83	0.124
38.00	3743.12	4357.68	30192.06	16374.	643.66	0.128
40.00	3881.51	4420.76	31553.08	15946.	637.25	0.132
42.00	4002.36	4471.88	32766.69	15591.	630.62	0.136
44.00	4107.47	4509.82	33827.47	15297.	623.79	0.140
46.00	4195.94	4532.06	34734.01	15056.	616.78	0.143
48.00	4268.57	4543.30	35489.31	14863.	609.60	0.147
50.00	4326.57	4546.26	36101.18	14710.	602.28	0.150
52.00	4371.59	4545.92	36582.59	14592.	591.31	0.153
			695069.2 = POWER/ELEMENT			

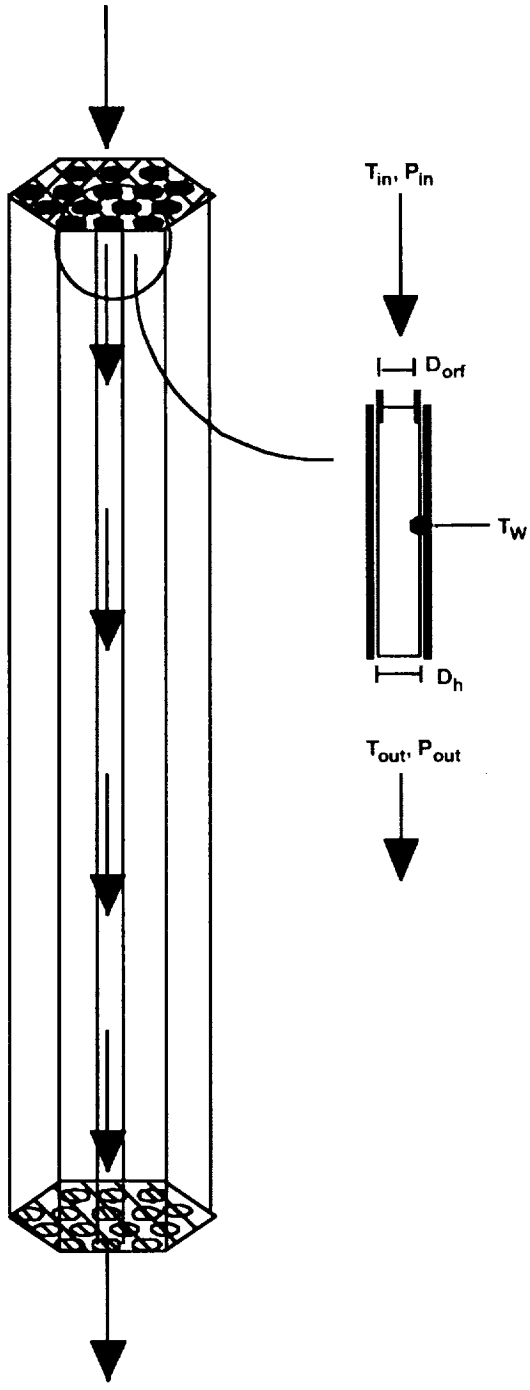

Figure 1.—Fuel element schematic diagram.

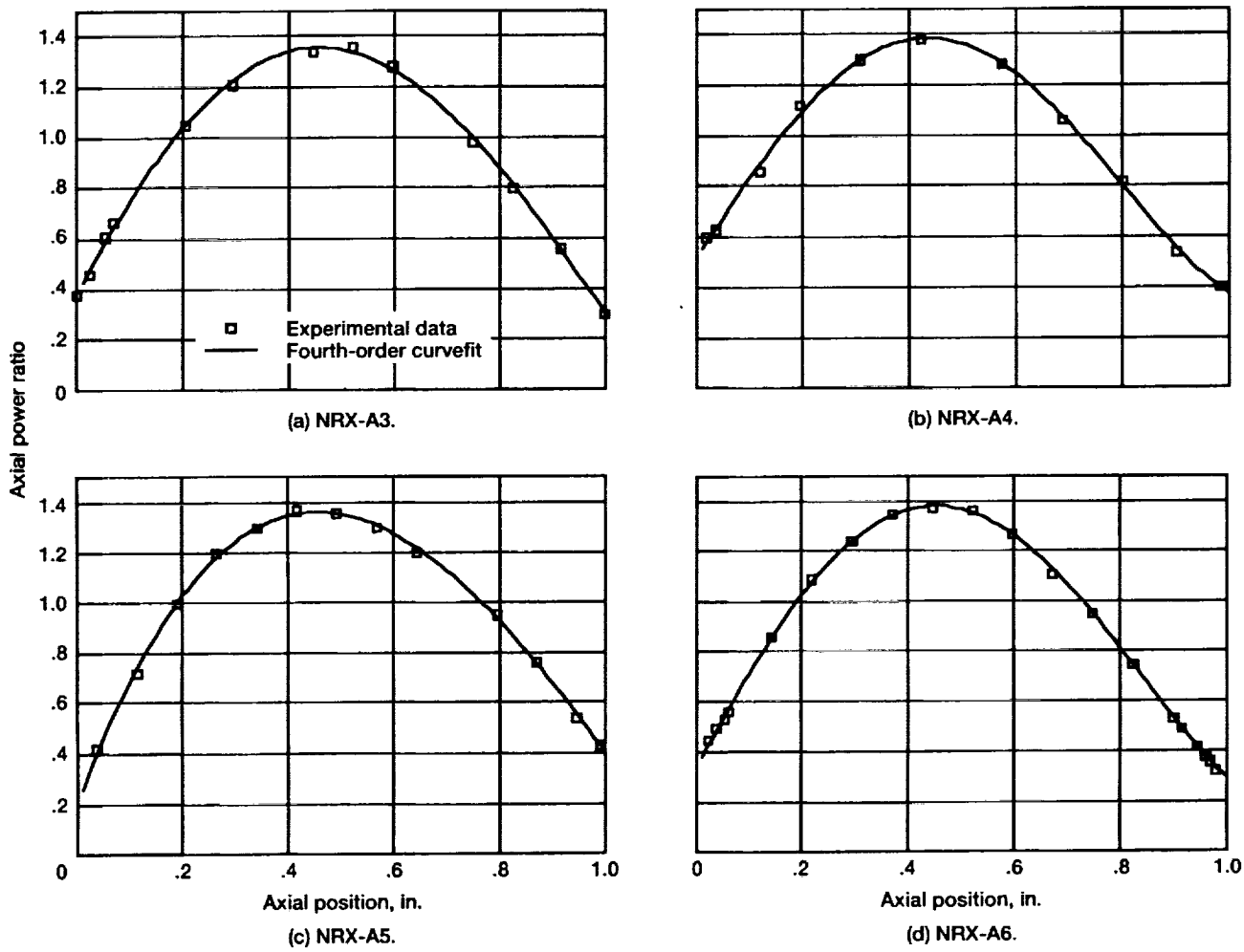

Figure 2.—Sample comparison of power shape factor curvefits to experimental data.

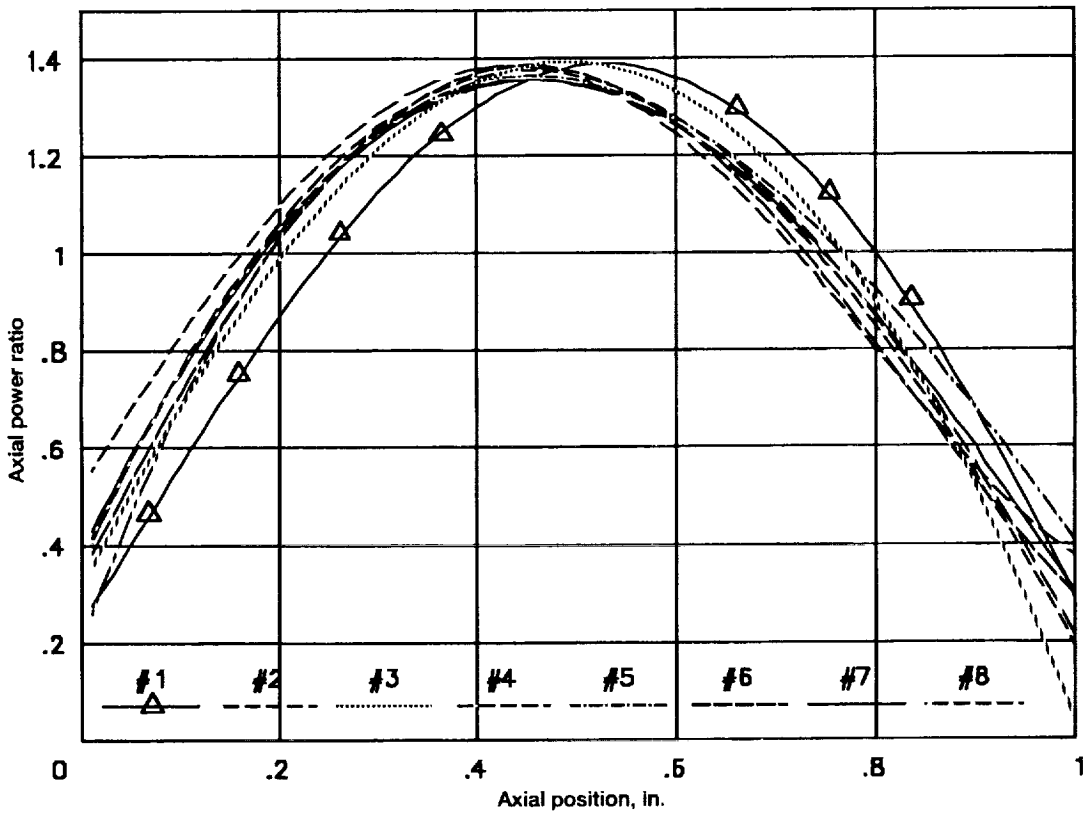

Figure 3.—Comparison of power shape factor curvefits for eight regression models.

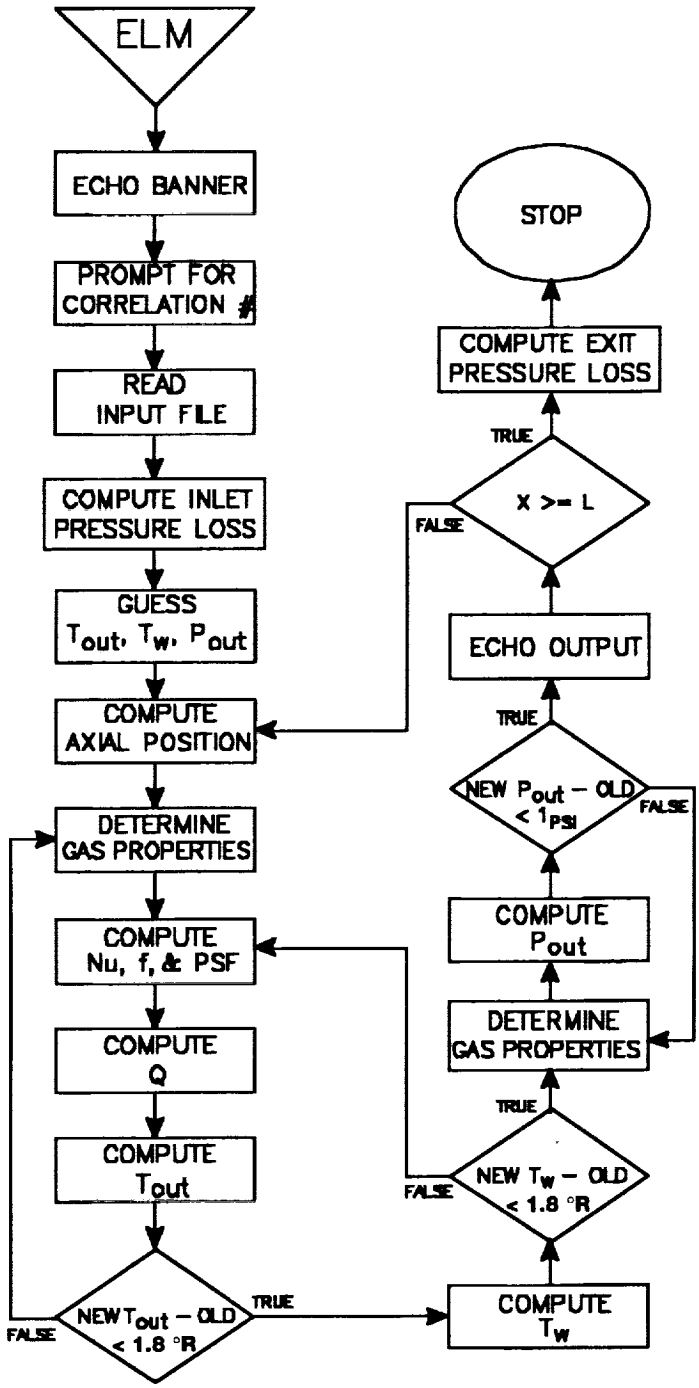

Figure 4.—ELM logic block diagram.

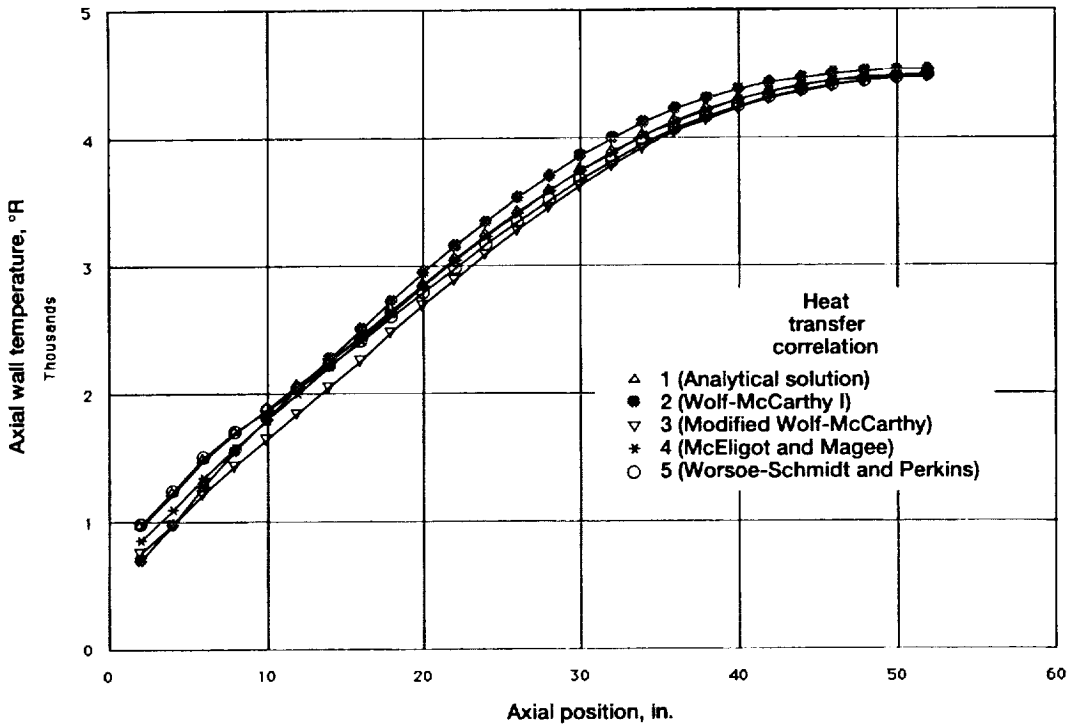

Figure 5.—Comparison of axial wall temperature distributions for heat transfer correlations 1 to 5.

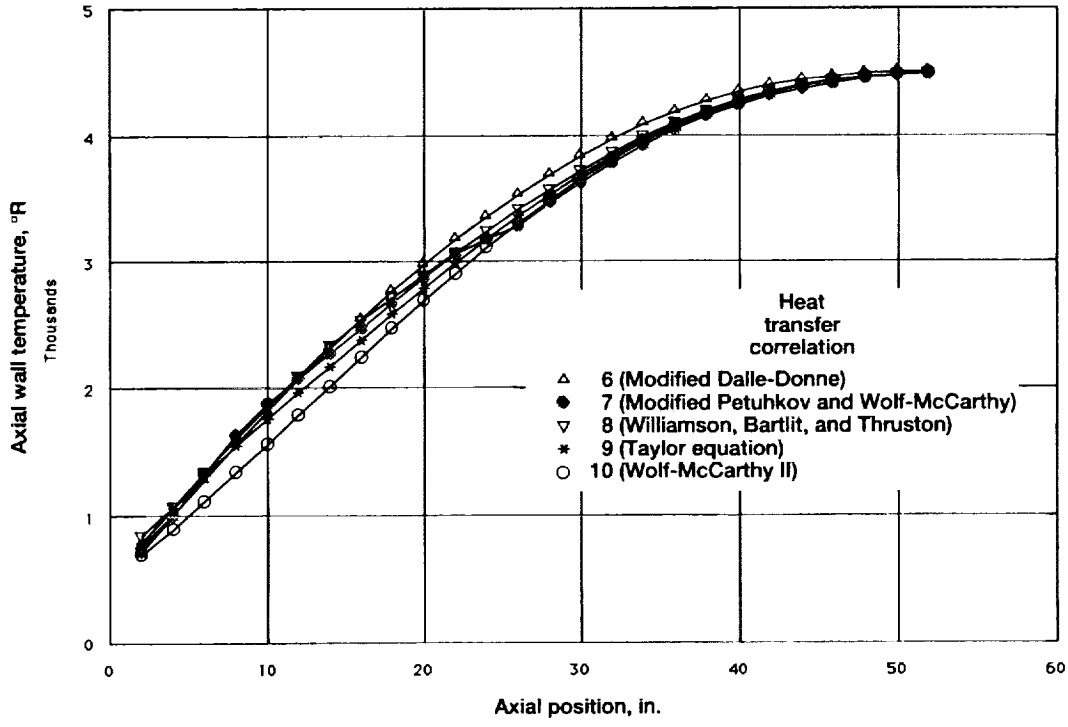

Figure 6.—Comparison of axial wall temperature distributions for heat transfer correlations 6 to 10.

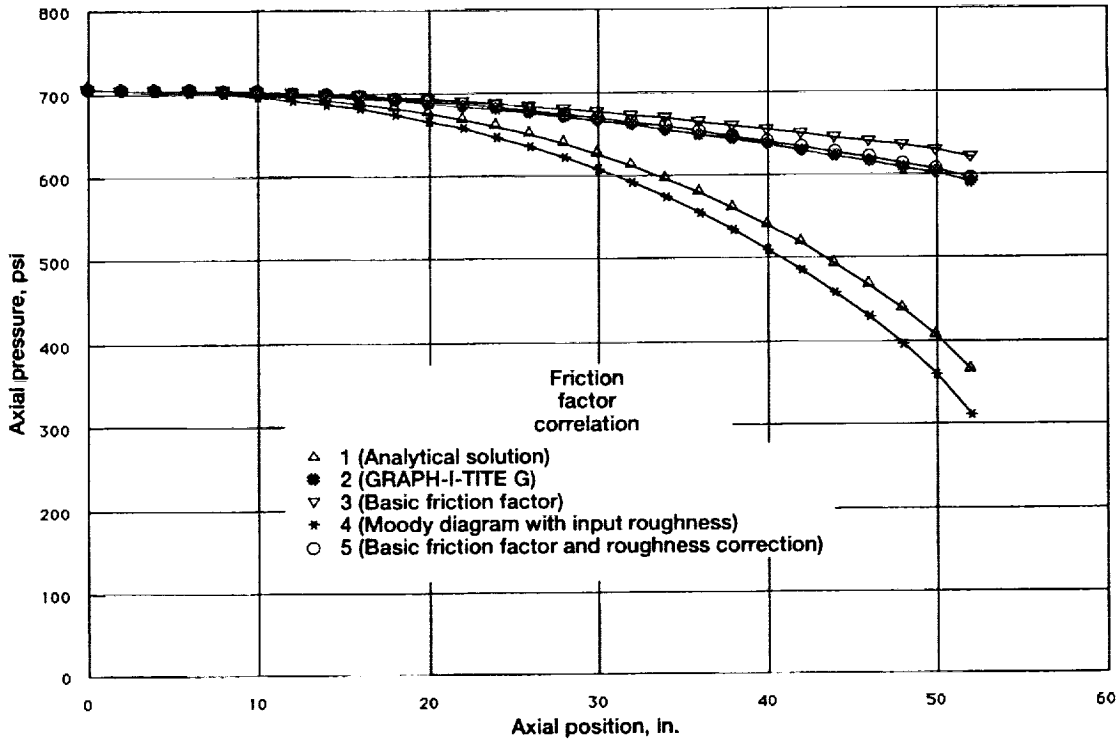

Figure 7.—Comparison of axial pressure distributions for friction factor correlations 1 to 5.

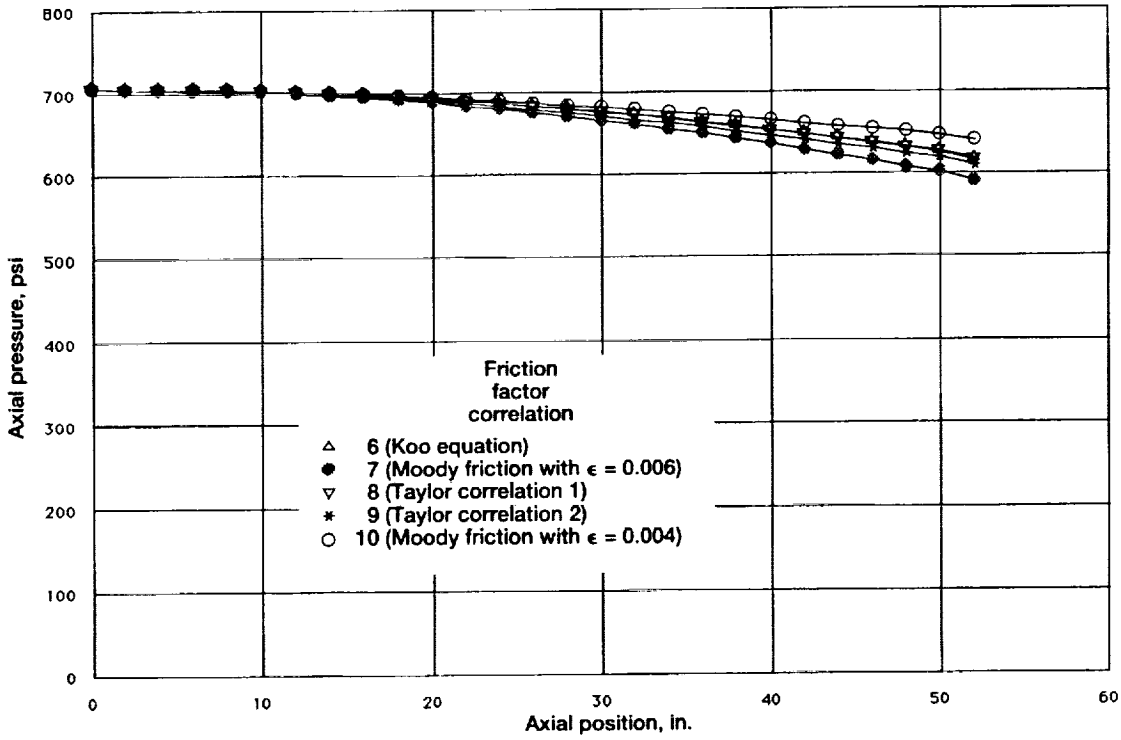

Figure 8.—Comparison of axial pressure distributions for friction factor correlations 6 to 10.

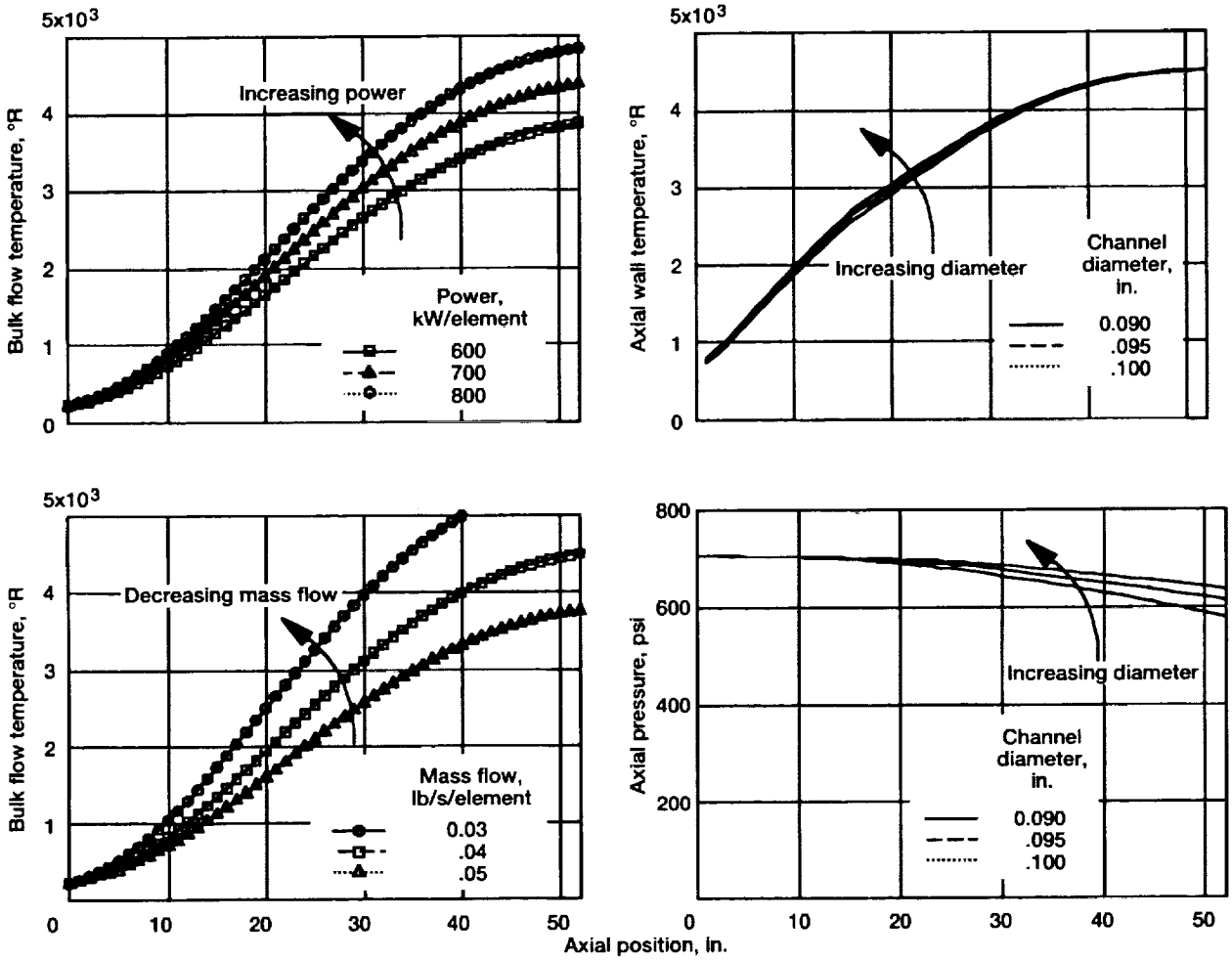

Figure 9.—Sensitivity to changes in various input parameters.

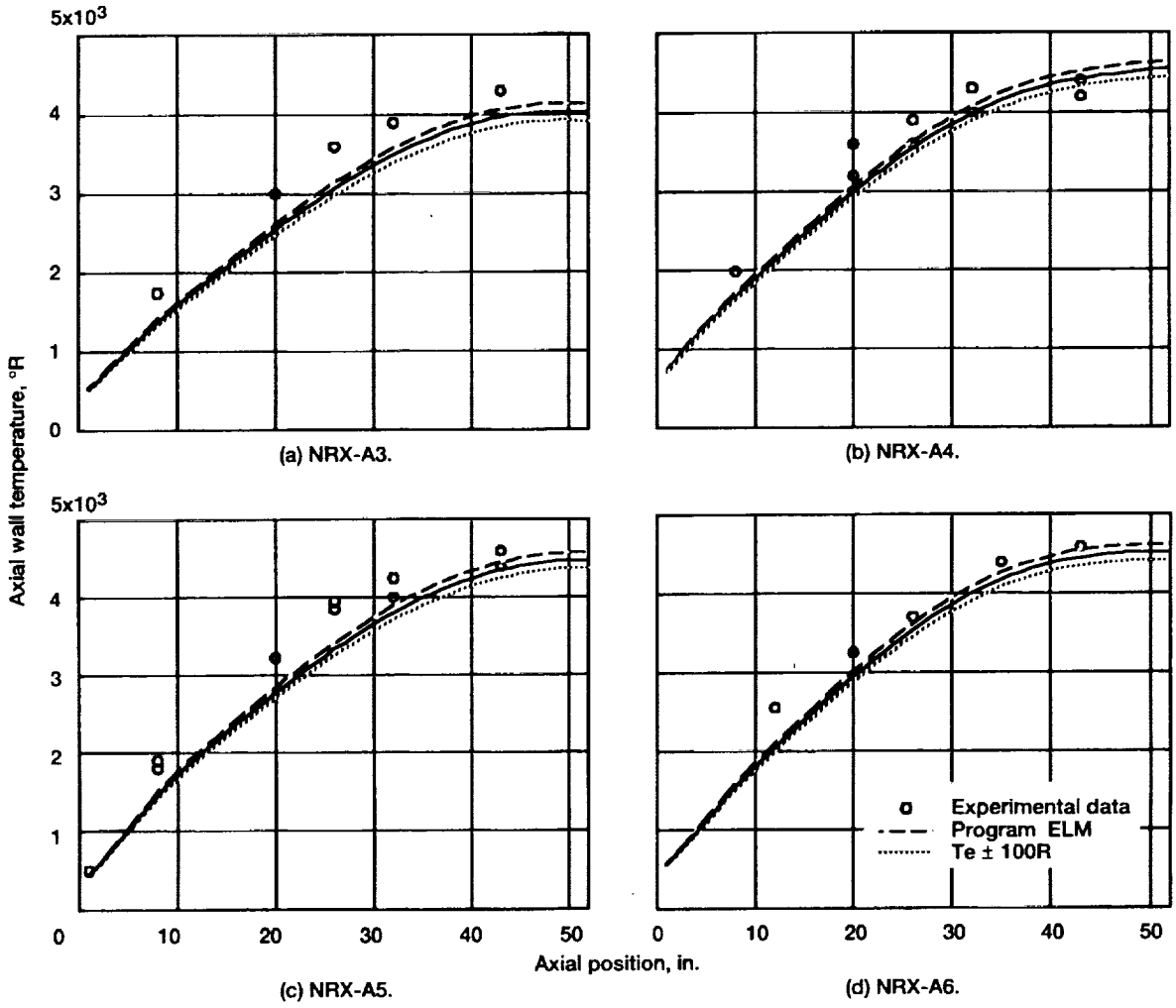

Figure 10.—Comparison of program ELM to experimental data.

REPORT DOCUMENTATION PAGE

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	November 1992	Technical Memorandum

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Program ELM: A Tool for Rapid Thermal-Hydraulic Analysis of Solid-Core Nuclear Rocket Fuel Elements

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13. ABSTRACT (*Maximum 200 words*)

This report reviews the state of the art of thermal-hydraulic analysis codes and presents a new code, Program ELM, for analysis of fuel elements. ELM is a concise computational tool for modeling the steady-state thermal-hydraulics of propellant flow through fuel element coolant channels in a nuclear thermal rocket reactor with axial coolant passages. The program was developed as a tool to swiftly evaluate various heat transfer coefficient and friction factor correlations generated for turbulent pipe flow with heat addition which have been used in previous programs. Thus, a consistent comparison of these correlations was performed, as well as a comparison with data from the NRX reactor experiments from the Nuclear Engine for Rocket Vehicle Applications (NERVA) project. This report describes the ELM Program algorithm, input/output, and validation efforts, and provides a listing of the code.

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